Evaluating the Fragmentation Data from Copper and Gold Mines

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Abstract

This paper presents a critical review of the fragmentation data obtained from some large open pit copper and gold mines. Database includes 35 mines with Uniaxial Compressive Strength values ranging from 19 MPa to 227 MPa (2756 psi to 32923 psi). Variation in the fragmentation data and the causes are discussed in detail. Quality assurance/quality control (QA/QC) in drilling and blasting was shown to have significant impact on fragmentation. In addition, controllable blast design parameters including drill pattern, powder factor, blast timing, stemming length, etc. as well as the large blast sizes have significant potential to improve fragmentation. Feed size requirements of crushing and grinding circuits were discussed in detail. The paper discusses the effects of different size fractions (top size, 80 % passing size and % passing 10 mm (0.5 in)) on the downstream processes and the role of the fragmentation model in the mine to mill process. Blast domains based on rock strength and structure can be established by using a fragmentation model which is calibrated using measured fragmentation data. This allows the blast engineer to compensate for changing rock characteristics and stabilize the ROM fragmentation size and result in increased crusher and mill throughput. Two case studies were presented to demonstrate the benefits achieved in downstream processes. Main benefits were reduced downtime at crusher circuits, improved mill throughput as well as reduced total operating cost. A simple relation between uniaxial compressive strength and powder factor was proposed using the database for the optimized mines as a guideline to allow site engineers to compare their sites against the other sites.

Introduction

Drill and blast is the most energy efficient and cheapest way of reducing particle size compared to crushing and grinding. The use of greater energy input in the blasting unit operation is less costly than expending the energy downstream. For a typical mine with primary crushing and SAG mill, the costs of drill&blast, crushing and grinding costs are 0.6, 0.8 and 5.0 $/t, respectively. Murr et al. (2015) suggests applying more energy in blasting to reduce the comminution energy (44 % used in comminution vs 7 % used in drill&blast). Adamson (2015) notes that the drill and blast function plays a pivotal role in controlling the total cost of producing the output that is sold. However, in order to make informed decisions concerning where to manipulate drill and blast costs, it is necessary to understand how drill and blast impacts on that final, product cost. An estimation of what optimization will mean in financial terms is necessary in order to justify an increase in unit operational costs.

Napier-Munn (2015) states that comminution, particularly grinding, is the largest consumer of energy on most base and precious metal mine sites. He suggests that there are several strategies that can be pursued to reduce comminution energy consumption including baseline studies, mine to mill, pre-concentration, high pressure grinding rolls (HPGR), alternative flowsheets and new technologies. Of these strategies, the author believes that improved fragmentation using high intensity blasting techniques, mine to mill, pre-concentration and alternative flowsheets utilizing HPGR’s are the most promising and available strategies to reduce the comminution energy and reduce the total mining cost. High intensity blasting technique usually involves increased powder factor selection in harder ore types to improve fragmentation (Workman and Eloranta, 2003; Dance et al., 2006, Esen et al., 2007; Katsabanis et al.,
Investigations by several researchers to date have shown that all the processes in the mine to mill value chain are inter-dependent and the results of the upstream mining processes (especially blast results) have a significant impact on the efficiency of downstream milling processes such as crushing and grinding. Numerous mine-to-mill projects to date resulted in mill throughput increases of between 5 and 30% depending on the ore strength and comminution properties (Dance et al., 2006; Esen et al., 2007; Kanchibotla and Valery, 2010; Esen, 2013; La Rosa et al., 2015).

This paper reviews the fragmentation data collected from 35 large open pit copper and gold mines with a view to compare the data sets and identify the causes of the variability. Feed size effects on crushing and grinding circuits are discussed briefly. The effects on the comminution circuit performance are shown by presenting two case studies. Heap leaching sites were not included in this study.

**Feed Size Effect on Crushers and SAG Mills**

Primary crushers are sensitive to oversize rocks because they cause hang-ups and also increase the power draw. It is generally accepted that the primary crushers reduce only the top size of run of mine and most of the fines (-10 mm) (0.5 in) are generated through blasting. The Key performance Index (KPI) is the Closed Side Setting (CSS) of the primary crusher. If the ROM fragmentation is finer, then there is a scope to minimize the CSS to deliver finer SAG feed. Equation 1 shows this relation (Bailey et al., 2009).

\[
F_{80} = 0.2 \times CSS \times DW_i^{0.7}
\]

*(Equation 1)*

Where:
- \(F_{80}\) = primary crusher discharge 80 percent passing size in mm (or AG/SAG mill feed)
- \(CSS\) = primary crusher closed side setting in mm
- \(DW_i\) = drop weight index from the SMC Test®

It is important to highlight that any mine-to-mill optimization work focuses on feed size to the SAG Mills (Dance et al., 2006). SAG mills require a certain ore feed size distribution to operate efficiently. This feed is supplied to the mill by the Primary Crusher, which is also influenced by the size distribution achieved from blasting. Significant effort has been spent at a number of operations to relate SAG mill throughput with SAG mill feed size. Very good correlations have been obtained demonstrating that the finer the top size and \(F_{80}\) of the mill feed, the higher the mill throughput. Figure 1 shows correlations between SAG mill feed size as measured by on-line image analysis systems and SAG mill throughput and specific energy consumption (kWh/t) at a copper ore operation (Dance et al., 2006).

The ideal size distributions, which result in maximum mill throughput and performance, will depend on the breakage characteristics of the ore (rock strength) as well as the operating conditions of the mill (lifter design, grate design, mill speed and rock charge). In general terms, higher throughput for these harder domains may be achieved when the SAG mill feed has (Dance et al., 2006):

- as fine a top size as possible;
- the smallest possible amount of 25 to 75 mm (1 to 3 in) intermediate size material and
- a maximum amount of −10 mm (0.5 in) fines.
The SAG mill feed top size is mostly controlled by the primary crusher. The intermediate size material which is usually in the size range between 25 to 75 mm (this range will vary according to ore hardness) is reduced both by appropriate fragmentation in the mine and optimal operation of the primary crusher. Fines (-10 mm or 0.5 in material) are largely generated by blasting. Depending on ore hardness, some fines can be also generated by inter-particle breakage in the crusher, especially when it is choke fed. The more fines in the feed, the higher the SAG mill throughput.

Fragmentation Modeling

Fines in blasting is considered as one of the most important KPIs in the mine-to-mill methodology. Mine-to-mill projects to date showed us that operations that require higher mill throughputs should maximize the amount of fines (-10 mm or 0.5 in fraction). These projects required an accurate estimation of fines and complete ROM fragmentation size distributions.

The Kuz-Ram model’s poor ability to describe the fines was one of the major reasons why the Two Component Model (Djordjevic 1999), the Crush Zone Model (Kanchibotla et al., 1999) and Onederra and Esen’s (2004) model were developed at the JK MRC in Australia. All combine two Rosin-Rammiller distributions or components, one for the coarse part of the curve and one for the fines. Onederra and Esen (2004) showed that the Kuz-Ram model is not able to satisfactorily predict the complete size distribution of fragments, particularly in the fine and intermediate size fractions. The model was later updated using Swebrec function (Esen, 2013). Figure 2 shows a calibrated model at a gold mine where a partial sieving data is available for a muckpile. The sieve sizes were 10mm (0.39 in) and 30mm (1.18 in). Image analysis was also carried out to determine the size distribution of the blasted muckpile. It is shown that the model results compare well with the measured data (Esen, 2013).

Key input parameters of the fragmentation model are rock properties (structure and strength); explosive detonation properties; and blast design parameters (hole diameter, bench height, burden, spacing, stemming length etc) (Esen et al., 2003; Onederra and Esen, 2004).

Fracture Frequency (FF) and Rock Quality Designation (RQD) give a good indication of the rock mass structure, which in turn will drive the proportion of coarse material in the blast fragmentation. Fines generation in the blast (material below a few millimeters) is mainly related to rock strength as well as explosive/rock interaction (Onederra and Esen, 2004). As the fine end of the ROM size distribution
Figure 2. Comparison of the sieve data at 10 and 30mm with the model curve has a direct impact on critical downstream processes, it is important to be able to accurately predict blast-induced fines so they can be controlled and their benefits exploited.

The Point Load Test is a well-known and widely used index to determine the rock strength. It is commonly used as a quick and simple method to predict Unconfined Compressive Strength (UCS). Rock samples may be in the form of core (diametral and axial tests), cut blocks (block test), or irregular lumps (irregular lump test). The irregular lump test offers the greatest convenience, as no sample preparation is required.

Once the PLI and RQD (or fracture frequency) data are available, the range of rock properties is mapped out to define possible blast domains, which are zones of ore with similar rock strength and structure that when subjected to blast generate similar fragmentation. A good example of a blast cookbook is given by Burger et al. (2006) as shown in Figure 3. In general, a cookbook shows the key design parameters including the drill patterns as a function of the rock hardness and structure. Main function of these cookbooks is to provide a consistent fragmentation F80 and top size for the downstream processes. Mine to mill study defines the target fragmentation size fractions.

![Figure 3. Drill and blast “cookbook” for mill feed ore (Burger et al., 2006)](image-url)
A Critical Review of the Fragmentation Data Obtained From Large Open Pit Copper and Gold Mines

In this study, fragmentation data from 35 mines is analyzed. There were 54 fragmentation data sets collected in these sites. UCS varied from 19 MPa to 227 MPa (2756 psi to 32923 psi). Powder factor range was 0.22 - 2.27 kg/m³ (0.37 – 3.83 lb/yd³). Figure 4a shows the box plot of the fragmentation data (F80, 80% passing size) for the sites before and after the optimization. It is shown that variability in the F80 (before optimization) was rather large when compared to the optimized F80. Figure 4b shows the histogram for the 23 sites in which the optimization studies were undertaken. Significant reduction in the F80 was seen in these cases. F80 dropped to less than 300 mm (11.8 in) except for a few sites.

![Box & Whisker Plot](image)

**Figure 4.** a) Box plot of the fragmentation data (F80) before and after the optimization projects  
   b) Histogram of the fragmentation data (F80) before and after the optimization projects

In one of the gold sites, F80 varied between 200 and 800mm in their 35 blasts in which fragmentation data was available (Figure 5). Certainly, this site was not achieving a consistent fragmentation. They achieved target F80 of 400mm in 57% of the blasts. This target was set before the mine to mill study.

In general, the variability in the fragmentation data can be explained in two groups as shown below based on the results of the optimization projects carried out by the author. Only major contributing factors are listed based on author’s experience. Two case studies presented (see next section) in the paper show some of the Quality Assurance/Quality Control (QA/QC) issues experienced at sites.
Figure 5. Measured fragmentation data at a gold mine

- QA/QC issues
  - Poor drilling control - hole depth, collar location
  - Inappropriate stemming material (drill cuttings, mill scats) and size
  - Poor loading practice (hose handling practices, top loading into wet holes, not loading to design stemming height, etc)
  - Lack of load sheets showing design and actual hole depths, backfills, explosive amounts and type, top-up
  - Pre-conditioning from earlier blasts (over-drills, limited burden relief, etc)
  - Inadequate bench preparation
  - Re-drills not being conducted (no tolerance limit for re-drills)
- Inappropriate selection of the blast design parameters
  - Inappropriate stemming length choice
  - Poor blast shape
  - Small blast size
  - Short bench height (stiffness ratio: bench height/burden being less than 2)
  - Inadequate powder factor and inadequate energy match to the ground conditions (rock strength and structure)
  - Incorrect explosive selection
  - Inappropriate delay time and/or tie-up
  - Loss of energy due to the cavity, hard/soft interfaces

All optimization studies conducted by the author involve a comprehensive drill and blast audit. The audit process includes below steps:

- Geology: lithology, alteration, weathering, grades, cut-off grades
- Mine planning: short term and long term plans, pit optimization studies, yearly target ore/waste productions
- Geotechnical: review of the geotechnical reports, ore/waste hardness and structure (window mapping, RQD etc), crest loss, toe gain, slope stability analyses, failures to date, water
Bench preparation: on-bench practices against best practice
Blast design: blast design templates used for ore/waste and final wall blasts, communication process, laser profiling, boretracking, survey data (topography, crest and toe lines data), management of re-drills and backfilling
Drilling: marking, drilling holes, drilled inventory, drill availability and utilization, equipment list with their specifications, as designed vs as actual hole locations and depths
Explosive charging: load sheets, explosive selection, as designed vs as actual stemming lengths, emulsion gassing, primer location and selection, blasted inventory, backfilling
Blast timing and tie-up: review of the delays used on-site, tie-up plans, sign-off, blast notification, guarding, exclusion zones, misfires and their management, dilution/ore loss management
Blast monitoring: blast videos, vibration and fragmentation measurements, flyrock review, post-blast inspection, backbreak/overbreak
Reporting: Blast summaries, costing, all paperworks with each blast, reconciliation, database updates

In this paper, powder factor changes before and after the optimization studies were analyzed. There were 40 cases out of 54 fragmentation data sets where powder factor and fragmentation data were available for both before and after optimization studies (see Figure 6). This is a useful graph for sites wishing to compare their sites against other operations. It is shown that sites increased the powder factors approximately by 50%.

![Figure 6. UCS vs powder factor for the optimized sites](image)

In the next section, two case studies are presented where mine to mill optimization projects were conducted. These studies show the benchmark case with areas of improvement. Following drill & blast as well as crushing/grinding recommendations, these sites achieved significant increases in mill throughput.

**Case Study 1 – Results from an Open Pit Copper Mine**
At one of the copper mines in Chile, a blast was audited in one specific ore type (more competent ore). The site was experiencing lower SAG mill throughput due to a higher proportion of ‘harder’ material. 41 photographs were collected for fragmentation analysis of this blast. Figure 7 shows the F80
distribution. It is shown that there is a significant variability in the data and coarse sizes are clearly seen (>300mm) (11.8 in). In this case study, key issues were variations in the hole location, hole depth and stemming length and stemming size.

![Figure 7. Histogram of the fragmentation data (F80) at a copper mine for one the audited blasts](image)

Figure 7 plots the histogram of the difference between actual and design hole depths: positive and negative values indicate over and under drilling, respectively. From these data, the actual hole depths averaged 1 m (3.28 ft) shorter than the design length. Under drilling in excess of 1 m will affect the blasting performance adversely – and this occurred on a number of occasions. Hole depths were in the range of 14.2 m (46.59 ft) to 19.0 m (62.34) (average: 17.6 ± 0.8 m) compared with the design of 18 m (59.05 ft).

Although charging sheets indicated that stemming was well implemented, almost in one quarter of the production holes, pocket charges in the stemming were not used as these holes were near mining equipment (shovels and drills). The lack of pocket charges in these holes contributed to the coarse fragmentation.

Actual burden and spacing values were measured to be 6.4 m (21 ft) ± 0.5 and 7.3 (23.95 ft) m ± 0.6, respectively (Figure 9) compared with the design values of 6 m (19.68 ft) and 8 m (26.25 ft). Burdens were generally more than 6 m design. Spacings were less than 8 m design. Some of the production holes were 1.9 m (6.23 ft), 3.8 m (12.47 ft) and 4.4 m (14.44 ft) apart (i.e. collaring position deviated from design point) causing S/B ratio being less than 1. Low S/B ratio and larger burdens are expected to result in coarser fragmentation.

Due to the significant variations in some key design parameters (collar location, hole depth, stemming length), a stochastic approach was taken in modeling blast fragmentation and these variables were input with a mean and standard deviation. This modeling approach uses Monte Carlo sampling followed by model simulation and results in envelopes of ROM size distributions. Figure 10 shows the impact of variations in blast design parameters on the fragmentation. The envelope of ROM distributions is shown by the lower 95% confidence level, the upper 95% confidence level and the average. The curves in Figure 10 show that the effect of deviations from the blast design are significant and affect the top size of the distribution more than the amount of fines. For these simulations, the 80% passing size varied from 259 mm (10.29 in) to over 1 m (3.28 ft).
Figure 8. Histogram of (measured - actual) hole depth. Negative values reflect short holes.

Figure 9. Histogram of actual burden and spacing values

Figure 10. Simulated impact of field implementation on fragmentation
With better QA/QC and increased powder factor selection (from 1.26 to 1.70 kg/m\(^3\)) (2.12 to 2.87 lb/yd\(^3\)) in harder ore types, the site achieved significant increase (15%) in throughput in harder ore type. Fragmentation model showed that F80 improved by 23.1% (from 376mm to 289mm) and -10mm material increased by 51.9% (from 14.24% to 22.06%). With finer ROM feed, the site reduced the CSS of the primary crusher which helped increase the throughput. JKSimMet Model simulation showed 12.5% throughput increase which predicted the measured result (15%) reasonably well.

**Case Study 2 – Results from a Gold Mine**

Case study 2 was from a gold mine in Ghana. This site has got a two-stage crushing circuit followed by two SAG mill lines. Main issue was that the site was 25% short of target mill throughput. Thus, an optimization study was required to achieve the mill target. Two production blasts were audited during the project. The blast audit identified several issues: a) Oversize in the top flitch caused by overdrilling from blasts above, poor stemming material, poor stemming length control b) Small blast sizes c) Inadequate bench preparation and re-drill issues d) Large variations in burden and spacing are causing non-uniform energy distribution (Figure 11) across blasts which could be addressed easily by fitting the drill rigs with high precision GPS units as well as a good bench preparation practice.

![Figure 11. Explosive energy distribution showing the variability in the energy levels](image)

Although bottom and middle flitches had finer F80 fragmentation (approximately 150 mm / 5.91 in), top flitches had F80 of approximately 380 mm (14.96 in). By having a better QA/QC process to address the issues given above, increased blast size and improved blast designs with higher powder factor (1.20 to 1.40 kg/m\(^3\)) (2.02 to 2.36 lb/yd\(^3\)), fragmentation improved significantly especially in the top flitch (Figure 12). With finer feed, crusher gaps were tightened which helped reduce the final product size. Following the changes in blasting and the crushing circuit, the mill F80 decreased from 40 mm (1.57 in) to 30 mm (1.18 in) and thus the mill throughput increased by 23% (from 475tph to 587tph) with the alternative blast design (Esen and Crosbie, 2011).
Conclusion and Future Work
Fragmentation data obtained from 35 large open pit copper and gold mines were reviewed. It is shown that variability in the F80 (before optimization) was rather large when compared to the optimized F80. Variation in the fragmentation data was due to a) QA/QC issues: for example, poor drilling control, inappropriate stemming material and size, pre-conditioning b) poor selection of the blast design parameters: for example; inappropriate stemming length, small blast size, inadequate powder factor, blast shape. Using the database, powder factor changes before and after the optimization studies were plotted against the UCS which is a helpful graph for site engineers. Before using this graph, it is recommended to audit the blasts for QA/QC and implement the recommendations from the audit for understanding the impact of QA/QC on fragmentation and establish the baseline before changing the controllable blast design parameters (e.g. powder factor, timing etc.).

Two case studies were presented which identified the causes of the variability in the fragmentation. Both QA/QC and the change in the controllable blast design parameters were needed to minimize the variability and improve fragmentation in harder ore types. Sites achieved consistent ROM feed by controlling the QA/QC and adopting the appropriate blast design parameters. These studies showed that the mill throughput increased by 15 % and 23 %, respectively for the Case Study 1 and 2. Understanding the variability in fragmentation and improving the fragmentation using the measurement and modeling can influence the productivity and costs at mines. A structured methodology based on the fragmentation modeling and measurement as well as a comprehensive audit at mines is fundamental to achieve the productivity and cost benefits.

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