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Fine grinding: How mill type affects particle shape characteristics and mineral liberation

Lucy Little*, Aubrey Njema Mainza, Megan Becker, Jenny Wiese

Centre for Minerals Research, Department of Chemical Engineering, University of Cape Town, Rondebosch, South Africa

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ABSTRACT

In minerals beneficiation applications, the main function of comminution circuits is to liberate valuable minerals to facilitate downstream separation processes such as flotation. Traditionally, design and optimisation of comminution circuits was based on the production of a target particle size distribution at an optimised throughput with consideration of energy efficiency and equipment wear rates. However, research in flotation and process mineralogy is leading to queries as to whether more should be demanded from the comminution circuit in terms of particle preparation. For example – if particle shape affects hydrophobicity, can mill operating conditions be adjusted to produce particles with shape characteristics which are more amenable to flotation? For this work UG2 ore (a South African platinum group mineral ore) was milled in a laboratory ball mill and stirred mill. To supplement the laboratory study, samples were taken from the fine grinding circuit of an operational UG2 concentrator. Automated Scanning Electron Microscopy with Energy Dispersive X-ray Spectrometry (Auto-SEM-EDS) was used for mineralogical and particle shape analysis of feed and product samples. Although the laboratory test work indicated a significant difference in product particle shape characteristics for the two mill types, the difference was not evident in the plant data.

1. Introduction

1.1. Background

With the continual depletion of high grade simple ore bodies, more complex, finely disseminated ore bodies are being processed, which has led to an increase in the prevalence of fine grinding (Sinnott et al., 2006). This has been evident in the platinum group element (PGE) industry in South Africa, where the Bushveld Complex hosts 70% of global PGE reserves. Since 1995, average feed grades of PGE ores being processed have dropped from around 6 g/t to less than 4 g/t (Mudd, 2012). From the early 2000s the industry invested in technology for fine grinding (Rule, 2011, 2010), simultaneously investing in technology for quantitative mineralogy to better understand the potential benefits associated with fine grinding (Gu et al., 2014; Rule and Schouwstra, 2011).

The first stirred mill was installed in the platinum industry in 2002, and by the year 2010, forty stirred mills had been installed at various platinum operations in South Africa, and these led to a step change in flotation recoveries (Rule, 2011, 2010). Over the last decade, approximately 200 Automated Scanning Electron Microscopy (Auto-SEM-EDS) systems have been installed worldwide. The contribution of these devices in facilitating the introduction of stirred mills at Anglo Platinum is used as a case study illustrating the value of process mineralogy (Gu et al., 2014; Rule and Schouwstra, 2011). It is apparent that both stirred milling and Auto-SEM-EDS technology have already made a valuable contribution in numerous minerals processing applications. However the industry still faces continual challenges, and improved understanding of fine grinding mechanisms, liberation response, and the role of particle shape has the potential to lead to further opportunities for optimisation. In minerals processing it is typical for significant process fluctuations, due to ore variability, to affect mill throughput and/or flotation grade and recovery. When these fluctuations cannot be explained by operational factors, they are typically ascribed to mineralogy or poorly understood factors such as particle shape. There is also currently increased interest in the effects of particle morphology on flotation performance, and questions being raised as to whether the shape characteristics of particles can be selectively modified using particular grinding conditions or different mill types (Guven and Çelik, 2015).

In a previous paper (Little et al., 2015), the authors developed a methodology for Auto-SEM-EDS shape characterisation, which was applied to data from laboratory fine grinding experiments with UG2 ore. The data presented indicated significant differences in shape

* Corresponding author.
E-mail addresses: lucyvanderuit@gmail.com, vtxluc001@myuct.ac.za (L. Little).

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characteristics between the major mineral components of the mill feed, with a high proportion of rounded chromite grains relative to the more angular silicates. After fine grinding, the chromite had very similar shape characteristics to the silicates, although significant differences were observed between the progeny of the two mill types (Little et al., 2015). This paper aims to explore these observations further, focusing on the two fine grinding devices and the breakage mechanisms there-in, size by size shape characteristics and valuable mineral liberation. Shape characteristics of samples taken from a UG2 ore concentrator are also analysed for comparison.

1.2. Fine grinding

As specific energy required for grinding increases exponentially with product fineness, energy efficiency is always a concern in fine grinding operations. Energy efficiency is probably the most significant advantage of stirred mills over traditionally used tumbling mills for fine grinding, and is likely to remain one of the dominant factors affecting decisions relating to mill design and operation. Whereas the energy intensity of ball mills is limited by the requirement for gravity to cause breakage, in stirred mills energy is imparted to the charge with an impeller, which allows for much higher energy intensities (Jankovic, 2003). In platinum group mineral (PGM) ore processing, stirred mills are used for both mainstream grinding applications at high throughputs, and concentrate regrind applications at low throughputs. In mainstream applications, an IsaMill (horizontally orientated mill) is typically installed as an optional tertiary grinding stage after primary and secondary ball mills. Vertical stirred mills such as the Stirred Media Detritor (SMD) or Vertimill are mostly used for concentrate regrind applications in the South African PGM industry (Rule, 2010).

The breakage mechanisms in stirred mills – regardless of the mill orientation – are typically described as abrasion and attrition (Gao and Forssberg, 1995; Sinnott et al., 2006; Wills and Napier-Munn, 2006; Ye et al., 2010), or more simply “shear” breakage (Radziszewski, 2013). The dominant breakage mechanism in ball mills is generally considered to be impact breakage in the toe of the mill, although recent DEM work has led to observations that low energy, repeated contacts in the bulk of the charge are dominant, causing damage accumulation and incremental breakage (Tavares, 2009; Weerasekara et al., 2013). Fig. 1 illustrates these breakage mechanisms and associated terminology, drawing attention to the manner in which breakage mechanisms can affect liberation. Understanding of these breakage mechanisms (which are dependent on ore characteristics), is important for modelling and simulation of comminution circuits for design and optimisation – particularly if effects on liberation are to be predicted. Approaches to studying these breakage mechanisms include computational methods such as DEM and CFD (Cleary et al., 2006; Sinnott et al., 2006; Weerasekara et al., 2013), as well as experimental methods where progeny size distribution, particle shape, and liberation characteristics are used to provide insight into the mechanisms (Frances et al., 2001; Gao and Forssberg, 1995; Hoşten and Özbay, 1998; Kaya et al., 2002; Palaniandy et al., 2008; Roufail, 2011; Varinot et al., 1997; Vizcarra et al., 2011; Ye et al., 2010). Most of this work has focused on relatively coarse grinding (> 150 μm), so understanding of breakage mechanisms in the fine grinding region relevant to PGM processing remains limited.

Cleavage is also sometimes classified as a breakage mechanism, although the term has different connotations in different fields. A generic description provided by King (2001) is that cleavage results when the original solid has some preferred surfaces along which fracture is likely to occur. In mineralogy, these preferred surfaces are planes of weakness within a crystal structure dictated by the atomic arrangement. The number and orientation of cleavage planes within a mineral are used as a diagnostic property for mineral identification. In mineralogy, fracture and cleavage are mutually exclusive – irregular breakage is considered fracture; breakage along regular surfaces related to the crystal structure is termed cleavage. Of the major gangue minerals in UG2 ore, chromite has no cleavage and orthopyroxene and plagioclase have prismatic cleavage.

Although understanding of breakage mechanisms is important for design and optimisation of comminution circuits, the progeny particle characteristics such as size distribution, shape distribution, and liberation characteristics play a fundamental role in downstream processing operations such as flotation. Understanding the possible effects of the breakage mechanisms in different mill types on these properties can therefore also make a valuable contribution.

1.3. Auto-SEM-EDS particle shape characterisation

At the particle sizes typically associated with fine grinding in minerals processing (< 75 μm), viable options for quantitative particle shape characterisation are limited, and effects of image resolution are of particular concern (Little et al., 2015; Varinot et al., 1997). Scanning electron microscopes provide higher resolution than optical dynamic image analysis devices, which enables analysis of finer particles. As the ore texture and mineral structure affect particle shape, the associated mineralogical information obtained with Auto-SEM-EDS is an added benefit of the technology.

Measurement and analysis of the full particle size distribution of a sample is necessary to understand and interpret effects of particle size, and being able to measure and represent particle shape with a distribution is similarly important. This is possible with the thousands of particle images obtained from Auto-SEM-EDS, using simple geometric descriptors (that do not rely on perimeter measurements), to assign a numerical value to each particle. *Roundness* is such a descriptor, which is the ratio of the cross sectional area of the particle, to that of a circle/sphere with a diameter equivalent to the maximum Feret diameter (Fe_{Max}) of the particle. The roundness descriptor used in this work is presented in Equation 1. It should be noted that some authors use the same name for other descriptors (Rahimi et al., 2012; Ulusoy et al., 2003). Issues relating to resolution, stereology, random orientation and uncertainty associated with Auto-SEM-EDS shape characterisation were addressed by Little et al. (2015).

$$Roundness = \frac{4\cdot Area}{\pi\cdot Fe_{max}^2} \quad (1)$$

1.4. Objectives

The objective of this work is to assess the influence of fine grinding in ball mills and stirred mills on valuable mineral liberation and particle shape characteristics of UG2 ore, a South African PGM ore. The work demonstrates how process mineralogy tools can be applied in a comminution context to provide insight into fine grinding breakage mechanisms in ball mills and stirred mills.

2. Methodology

2.1. Overview

The bulk of the work for this study was done at the laboratory scale, which involved batch grinding of UG2 ore in a ball mill and in a stirred mill. These experiments were effectively conducted in parallel, with representative samples of the same feed being milled in each device to two target product size distributions: ‘fine’ (28% passing 10 μm) and ‘ultra-fine’ (40% passing 10 μm). Mineralogical analysis of product samples was carried out using QEMSCAN, investigating bulk mineralogy, particle shape, base metal sulfide (BMS) liberation and platinum group mineral (PGM) liberation. To complement the laboratory data on shape, samples were taken from a plant-scale UG2 fine grinding circuit with a ball mill and IsaMill operating in series. This was to determine whether the findings relating to particle shape from the batch laboratory grinding data would be consistent with plant scale operations. It