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Characterisation of superficial breakage using multi-size pilot mills

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ABSTRACT

Low energy surface breakage has a high frequency of occurrence and thus plays a significant role in grinding processes. Yet this superficial breakage is poorly understood, measured and modelled – forming the focus of this work.

Pilot mills of 0.8–1.8 m diameter, designed to provide a predominantly surface breakage environment with efficient removal of the resultant progeny, are utilised to characterise superficial breakage. A new rate, that of superficial breakage ($1/(\text{kW h/m}^2)$), is introduced which measures fractional superficial breakage rate per energy provided to the surface of the material. This methodology is proposed as being suitable for understanding and characterising the surface breakage behaviour of ores.

Tests were conducted on two ores with different hardness. Superficial breakage rates varied from 2 to 16 ($1/(\text{kW h/m}^2)$) for the different ores and mill sizes, indicating a good sensitivity to ore type and the need to understand the applied stress – related to mill size. The results show that a single 'surface breakage rate for use in mill modelling is incorrect as the rate of superficial breakage is dependent on the size of the mill and therefore the inter-particle stressing conditions.

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Nomenclature

E_{ss}	surface specific comminution energy (kW h/m^2)	$R(t)$	superficial breakage rate ($1/(\text{kW h/m}^2)$)
$m(t)$	mill holdup at time t (kg)	t	grinding time (min)

1. Introduction

Treating low grade and more competent ore together with a continual increase in energy and operating costs is a principal challenge of the mining industry. Since comminution is the most energy intensive component of mining (Ballantyne and Powell, 2014), optimisation is crucial to keep the operation economically viable. This requires fundamental understanding of the underpinning mechanisms of size reduction in order to successfully develop and implement mechanistic models such as the Unified Comminution Model (UCM) (Powell, 2006), and the Virtual Comminution Machine (VCM) (Cleary et al., 2008). It is, therefore, vital to experimentally test breakage mechanisms that occur in full scale comminution processes. This will facilitate the modelling of any comminution device using computational modelling in combination with results of sophisticated ore characterisation tests (Barrios et al., 2011b; Powell, 2006).

1.1. Ore breakage characterisation

Although there are inconsistencies in definitions in the literature for breakage mechanisms, it is generally agreed that particles can be broken through single impact, multiple impact, superficial breakage which includes surface chipping and abrasion, and through an accumulation of each or all of these (Carvalho, 2013; Powell and Weerasekara, 2009; Tavares and de Carvalho, 2009). Ore characterisation testing relevant to each of these mechanisms should, therefore, be implemented in order to predict the progeny of rocks when they break under each mechanism. There are a number of different approaches in characterising breakage behaviour of ores.

The proposed standard breakage characterisation tests and tests which have been used in research studies can be grouped into single particle breakage, breakage in grinding mills and bed breakage. A selection of these tests are presented in Table 1.

Fig. 1 presents common breakage tests which are in use for characterising ore response at each stage of size reduction together with an approximate range of size of particles used in each

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characterisation test (Verret et al., 2011). K_{80} is the 80% passing size in mm.

It is evident from Fig. 1 that there are at least 9 characterisation tests which are commonly used in the design and modelling of Autogenous grinding (AG) and Semi-autogenous grinding (SAG) mills. In addition to the standard tests presented in Fig. 1 many characterisation tests have been implemented in research studies and should be added if found appropriate. The significant number of characterisation experiments is probably due to the complexity of the comminution process in AG and SAG mills (Verret et al., 2011). Single tests are not capable of providing an adequate understanding of comminution mechanisms and are unable to deliver the full and appropriate data required for design and modelling. Detailed understanding of the individual breakage mechanisms that occur in each comminution device can possibly reduce the number of characterisation tests that are required to describe the milling process. This can then provide accurate data required by mechanistic breakage models such as the UCM (Powell, 2006), the VCM (Cleary et al., 2008), and other mechanistic grinding models (Carvalho, 2013).

1.2. Characterising superficial breakage behaviour

The DWT and JKRBT® developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC) are well established for characterising the behaviour of ores in impact breakage (Morrison et al., 2007; Shi and Kojovic, 2007). However, there is no such robust methodology for characterising superficial breakage or abrasion behaviour of material provided in the literature.

In the mineral processing context, characterisation methods introduced in the literature as an ‘abrasion’ test (Devasahayam, 2013; Khanal and Morrison, 2008; Loveday and Naidoo, 1997; Napier-Munn et al., 1996) are often grinding tests with combined abrasion, superficial breakage and body breakage. Although the proposed ‘abrasion’ tests are designed to promote superficial breakage and abrasion, because they operate in batch mode, and thus re-breakage of progeny cannot be prevented. Consequently, small progeny particles will experience body breakage while being nipped between large particles – as in any ball mill. Also, high mill speed (i.e. above 60% of critical speed) and in some tests feed with a wide range of size distribution (Loveday and Naidoo, 1997; Napier-Munn et al., 1996) will promote the probability of body breakage. Fig. 2 illustrates charge motion simulated using Discrete Element Method (DEM) in a 1.8 m mill with 60 mm lifters having a 60° face angle, operating at 75% critical speed and holding a charge with a wide size range (i.e. $-250+6$ mm). The schematic shows active comminution mechanisms in such a condition. In the high energy impact zone, there is a high probability of particle fragmentation (i.e. Body breakage) due to direct impact of particles or small particles being captured between two coarse particles. In the low energy impact zone, the dominant mechanism of breakage will be surface breakage for coarse particles while there will still be a chance for small particles to undergo fragmentation by becoming caught between coarse particles.

A slow mill speed can be used to eliminate the high energy impact zone and a narrow feed size distribution can prevent body breakage of small particles nipped between coarse particles. Fig. 3 illustrates the charge for the same mill as Fig. 2 operating at 40% of critical speed and a charge with narrow size range (i.e. $-73+31.5$ mm). The schematic shows the active comminution mechanisms, and that the dominant one will be surface breakage.

The authors are trying to understand and model superficial breakage through a new approach conducting a surface (superficial) breakage grinding test in pilot mills, along with the study of single particle incremental superficial breakage in the JKRBT®. These studies are supported by DEM simulations. This should lead to an ore characterisation experiment which can provide data required for the design and modelling of AG and SAG mills plus any other devices that apply superficial breakage. This paper introduces the superficial breakage grinding test and methods implemented to analyse superficial breakage behaviour of rocks. Integration of single particle incremental breakage characterisation and modelling superficial breakage forms an ongoing research programme and its outcome will be published in future papers.

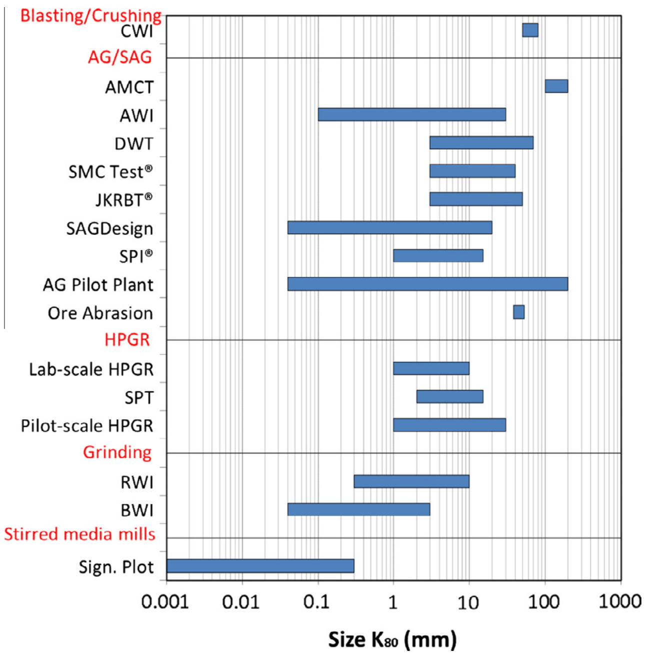

Fig. 1. Common breakage characterisation tests and approximate range of particle size testing (modified from Verret et al., 2011).

Table 1
Ore breakage characterisation tests based on test methods.

Single particle breakage	Crusher work index (CWI) (Bond, 1947)
	JK drop weight test (DWT) (Napier-Munn et al., 1996)
	SMC Test® (Morrell, 2004)
	JK rotary breakage test (JKRBT®) (Shi et al., 2009)
	Short Impact Load Cell (SILC) (King and Bourgeois, 1993; Tavares and King, 2004)
Grinding in lab/ pilot mills	Advanced media competency test (AMCT) (Siddall and White, 1989)
	Autogenous work index (AWI) (MacPherson and Turner, 1978; McKen and Chiasson, 2006)
	SAGDesign (Starkey et al., 2006)
	SAG power index (SPI®) (Starkey and Dobby, 1996)
	AG Pilot Plant (MacPherson and Turner, 1978)
	JK Ore Abrasion (Napier-Munn et al., 1996)
	Pilot abrasion test (Loveday and Naidoo, 1997)
	Rod mill work index (RWI) (Bond, 1960)
	Ball mill work index (BWI) (Bond, 1960)
	Sign. Plot (Burford and Niva, 2008)
Bed breakage	Lab-scale HPGR (McKen et al., 2001)
	Static pressure test (SPT) (Bulled and Husain, 2008)
	Pilot-scale HPGR (Klymowsky et al., 2002)
	HPGR compressed bed breakage test (Dundar et al., 2013)
	Crushing compression test (Evertsson and Bearman, 1997)
	Impact on mono-dispersed unconfined beds (Barrios et al., 2011a,b)

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