Minerals Engineering 100 (2017) 211–222

Contents lists available at ScienceDirect

Minerals Engineering

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

Investigating the effect of applied strain rate in a single breakage event

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ARTICLE INFO

Article history:
Received 18 May 2016
Revised 15 September 2016
Accepted 21 September 2016

Keywords:
Breakage
Strain rate
Fragments
Compression
Impact

ABSTRACT

For successful mechanistic modelling of any size reduction equipment, an understanding of the fundamentals of the breakage mechanisms is essential. This understanding will allow the comparison of breakage events and the quantification of the effect of key factors such as applied strain rate, particle size, and particle shape while they are isolated. This paper uses the concept of analysing breakage of a single particle as a multi-stage process to compare different breakage mechanisms and to quantify the effect of factors such as applied strain rate. This approach regards a single breakage event as a process affected by three sub-processes; first (or primary) fracture, capture and spatial distribution of fragments. The first fracture is assumed to be independent of breakage mechanism and to be a characteristic of the ore type. On the other hand, capture and spatial distribution are influenced by the characteristics of breakage environment, the kinetic energy of fragments and their brittleness. The focus of this paper is to examine how each sub-process of a breakage event is influenced by applied strain rate and its impact on the size distribution of progeny. In this work, three rock types of widely different strength and brittle behaviour, i.e. LKAB magnetite ore, Beaudesert silicate and Bundaberg quartz, were tested at various energy levels using the impact and compression breakage mechanisms. To isolate the effect of spatial distribution of fragments, particles were forced to remain in the breakage zone. In this condition, similar progeny size distributions were generated from compression and impact mechanisms at similar energy levels. However, allowing natural distribution of fragments produced coarser progeny from the compression of silicate.

1. Introduction

Comminution models are rapidly reaching a point that will enable them to explain the complete physics of a breakage process. Achieving this objective requires that the mechanistic models fully isolate the comminution environment from the effects of rock characteristics in response to different breakage mechanisms.

An example of such models is that developed by Barrios et al. (2011) to describe breakage of particles contained in a bed that is impacted by a falling weight on the basis of breakage of single particles. The milling environment in this model is described based on a mass of particles captured and the energy split within a mono-sized and monolayer bed as a function of particle size, impact energy and contact geometry of falling balls. The model takes into account the fundamental properties of the rock such as particle fracture energies and the fracture probability and is a key component of a mechanistic ball mill model (Carvalho and Tavares, 2013). Also, the unified comminution model (UCM) that is also envisaged as a mechanistic approach, tackles the underlying causes of ore breakage. One of the hypotheses that the model is based on is that comminution is a generic process of ore breakage in a range of modes and independent of the equipment that imparts it, so should be modelled as a fundamental process. In addition, if rock particles are fragmented according to the fundamental modes of breakage that exist in comminution devices, the overall product for any given device can be calculated by correctly combining the products of the individual modes of breakage (Powell et al., 2008). As is evident, the new trend of mechanistic models seeks the properties that reflect the response of rock particles to a breakage event independent of the properties of the breakage environment. One of the advantages of such models is their ability to decouple the properties of the rock from the environments in which comminution takes place. Thus, considerable efforts have been put in the last few years in the area of ore breakage characterisation in order to comprehend and unlock a single breakage process that has been treated as a black box event in the majority of conventional methods.

Rock fragmentation has a wide range of physical relevance including, but not limited to, rockburst, earthquake, blasting, crushing and milling. In these cases, fragments are produced under various ranges of applied strain rate (Lankford and Blanchard,

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http://dx.doi.org/10.1016/j.mineng.2016.09.010
0892-6875/© 2016 Published by Elsevier Ltd.

1991). The applied strain rate is defined as the rate of deformation that is applied by the comminution device. Generally, it is categorised into static, quasi-static and dynamic with the lowest rate belonging to static loading. Blasting operates a high range of loading from 10^2 s^{-1} to 10^4 s^{-1} and is considered a dynamic mechanism of breakage. However, the mechanism of breakage inside common ore comminution devices takes place in far lower ranges. Common comminution devices deal with loading at rates such that the duration of the contact is sufficient to allow the stress to propagate and equilibrate throughout the particle (Tavares, 2007). As a result, these techniques are called "quasi-static". High pressure grinding rolls (HPGR) and crushers use compression force to break down particles rather than the typical impact forces employed in tumbling mills. The compression velocity in HPGR ranges from 0.05 m/s to 0.1 m/s. On the other hand, the applied rate of loading in tumbling mills ranges from half a meter per second to a maximum 10 m/s. Fig. 1 illustrates the applied strain rates associated with different types of loading and equipment. It is important, thus, to investigate the effect of applied strain rate on the breakage properties of rock using the knowledge that has been gained by understanding a breakage event. This is particularly important due to its application for various comminution devices that operate within a relatively broad range of speed.

The effect of applied strain rate was first studied in the field of rock mechanics and the study of rock failure mechanisms. Table 1 provides a summary of some relevant studies in this field. As it suggests, the effect of applied strain rate appears to be significant when the material under investigation exhibits inelastic behaviour, such as marble, limestone, and some synthetic materials. For brittle materials, this effect is nearly always absent, unless samples are compressed at a very high rate. Also, fracture properties such as crack propagation, fracture energy, and force of such brittle rocks are independent of the rate at which the particles are broken.

Previous studies agree on the negligible influence of applied strain rate on brittle elastic material that is the area of interest for comminution processes (Antonyuk et al., 2005; Schönert, 1988; Tavares, 2007; Yashima et al., 1979). Also, evident from Table 1, most studies in the past have focused on the phenomenon of fracture and few attempts were made to study size distribution of fragments under various applied strain rates and to what occur after the first fracture. One interesting work that sheds light on the subject was carried out by Bergstrom (1962), who used a steel retaining ring to surround each particle while it was being crushed. When the ring was not used, the fragments flew in all directions. They also found that the fragments were coarser than those retained in the steel ring. According to Schönert (1996), secondary breakage is determined strongly by the spatial arrangement of the fragments after the first fracture. If the fragments stay narrowly together, then the reaction force becomes large. Based on this study, the expansion of the pile of fragments depends on the material hardness, the arrangement of the initial particles and the loading velocity. The harder the materials, the faster the velocity at which the fragments fly away. Hence, quartz fragments are distributed widely, but gypsum fragments form a narrow pile. The spatial distribution of rock particles is related to the system geometry; described by the impactor and anvil geometries and was addressed by Tavares (1997). He studied the effect of drop weight geometry on rock characterisation at equivalent energy levels using three geometries: ball-ball, ball-flat and flat-flat. The results indicated that at low energy impacts, the three geometries produced nearly the same size distribution of the progeny. In this case, it was understood that a large fraction of input energy was consumed to cause the first fracture on the parent particle and only a small amount of energy was left available to cause further breakage. However, when the input energy increased, the effect of geometry became more evident. The results showed that flat-flat geometry caused the appearance of a narrow size distribution of the progeny with a small percentage of fines whereas the ball-ball geometry produces a wider distribution of progeny sizes with a larger amount of fines. This is due to the amount of available remaining energy after the initial fracture which is consumed for progressive breakage. Flat-flat geometry involves a larger active zone of breakage that captures more material for breakage as fragmentation progresses.

Despite the relevance of the previous studies to the present work, it is important to explore beyond the first fracture properties of material to investigate rock fragmentation, which is the area of interest in the field of comminution. Yet, a fragmentation event has been treated as a lumped breakage process in many studies in the field of comminution. In this regard, the contribution of the first fracture properties of rocks in the final size distribution of products should be separated from the others in response to the applied strain rate. Isolation of fracture characteristics of particles from the environment that applies stress was first attempted by Schönert (1972). This approach considers a grinding machine as a system that applies a distribution of loads on single particles. Particles within this system break with the distribution of breakage energies and form a breakage product distribution. This approach has been picked-up by a number of researchers since the 1990s in the form of the present-day mechanistic mill models (de Carvalho and Tavares, 2013; King and Bourgeois, 1993; Powell et al., 2008).

The present study analyses a single breakage event as a process that begins with first fragmentation and continues as a series of secondary fragmentations, following the approach proposed by the authors in a recent publication (Saeidi et al., 2016). As such, the effect of applied strain rate on breakage characteristics of rocks was analysed in light of its effect on each sub-process. For this purpose, a carefully planned experimental work was conducted that isolated the effect of each sub-process, including first fracture,

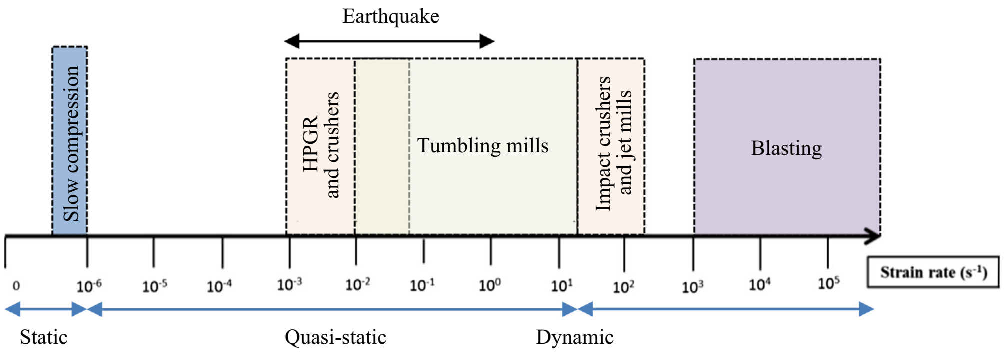

Fig. 1. Strain rates associated with different types of loading.