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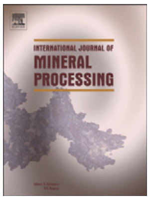

Introducing the concept of mechanical texture in comminution: The case of concrete recycling

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ABSTRACT

Modern comminution research and development are mainly product driven rather than material driven. An opinion that is gaining acceptance throughout the comminution community is that it is desirable for the comminution field to evolve toward material driven process design. To this end, this paper introduces the concept of mechanical texture, which corresponds to those textural properties of materials that have a direct bearing on their mechanical and fracture properties, which in turn should be the primary target for comminution process research and equipment design. The paper shows that mass specific fracture energy *Ecs* is a fracture parameter that is highly sensitive to variations in material texture, leading to selecting *Ecs* as a sound mechanical texture index. The paper then shows that, in the case of concrete, a set of specific features of the fracture porosity that can be measured inside concrete texture correlate highly with *Ecs*, thereby defining mechanical texture for concrete comminution. The demonstration that it is possible to establish a direct link between textural properties of concrete and macroscopic properties relevant to comminution shows that material driven comminution process modeling and design are possible and should be encouraged.

1. Introduction

Size reduction has been a pivotal process in the production of metals for as long as can be remembered, for beneficiation of minerals and waste. Size reduction unit operations are used throughout the minerals industry for the purpose of liberating valuable minerals, creating reactive surface area and producing desirable particle size distributions. As stated by Lynch in his introductory statement to his acclaimed 1977 textbook, "*the extent to which breakage must proceed depends on the fineness of intergrowth or the "natural grain size" of the valuable particle. The natural grain size may vary widely…*" (Lynch, 1977). This statement is perhaps one of the most important statements made in the early days of comminution modeling, as it recognizes the significance of ore texture in the size reduction process, and emphasizes its natural variability.

Surprisingly, despite the strong significance of material properties implied in Lynch's statement, the path which comminution research has followed since has by and large diverged away from the material to be processed. Neither has it been focusing on the process undergone by particles inside comminution unit operations, but has been dedicated to modeling and predicting the product output from the unit operations. This approach to comminution modeling and optimization has permitted formalization of a coherent and useful framework for what was prior an "empirical art", thus taking mineral comminution to an entirely new level. Over the past 4 decades, comminution research has served the industry well, giving it the means to increase production rates and meet society's needs. Comminution research did produce major conceptual advances, of which the most significant perhaps are the energy specific size reduction relationships, the breakage and selection functions for application of the population balance model to mineral comminution modeling, and the development of advanced simulation environments and control systems. And yet, the focus of comminution research and development has not been the ore itself, which finds itself embedded into sophisticated comminution models through some averaging property, distant from its actual physical properties and the variability thereof.

In accord with a number of researchers who have looked at the material contribution in comminution, such as Gaudin (1939), Schönert and Marktscheffel (1986) and Yashima et al. (1987), Powell et al. (2008) have formed the opinion that this comminution modeling approach has now reached an impasse, in that it can no longer evolve to meet the expectations of a modern mineral industry whose future depends on its ability to juggle scarcer and poorer ore bodies, rising energy costs, increasingly stringent environmental constraints, competition for access to water and fast changing societal needs. In order that the mineral industry can meet such a complex equation, Powell et al. propose a unified vision of comminution modeling, which some may consider as a paradigm shift relative to current practice. This vision focuses on the process itself, with the ambition of describing and predicting every individual event that occurs when comminuting an ore, down to the level of individual particles. This approach repositions the material to be processed to the heart of comminution modeling, which comes back to Lynch's statement cited above. This vision is largely fueled by the recent ability to simulate, with millions of objects, individual events that occur

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inside comminution machines in operation (Cleary, 2004, 2013; Cleary and Morrison, 2011; Weerasekara et al., 2013). In retrospect, it is fair to recognize that such capabilities were nonexistent and inconceivable when modern comminution modeling research emerged, which justifies the path taken by comminution research. Being able to simulate individual stress events inside a full scale comminution machine means, in turn, that physical properties of mineral particles relevant to comminution must be identified and modeled. Hence, relating mineral texture of a particle to the manner in which it fractures under stress is one critical issue in Powell et al.'s vision of the future of comminution modeling.

Prediction of the fragmentation behavior of a mineral particle under stress from knowledge of its texture is one of the key ingredients to Powell et al.'s vision of the future of comminution modeling. There are a number of steps to achieving this, of which the following 3 are perhaps the most significant:

Step 1 Measurement and modeling of the *mineral texture,* which is a spatial description of the components that make up the texture of the ore. Texture modeling for the purpose of enacting Powell et al.'s unified comminution model requires means for quantifying and reconstructing particle texture in three dimensions.

Step 2 Identification of the textural components responsible for the mechanical/fracture behavior of the texture under stress, whose combination define what is here referred to as *mechanical texture*. The concept of *mechanical texture* embodies the direct link between mineral texture and the mechanical/fracture behavior of the ore under stress.

Step 3 Simulation of the fracture of a mineral particle with known mechanical texture under given loading conditions (Weatherley, 2013). This 3rd step provides the link between ore texture and DEM modeling for predicting the outcome of comminution processes.

The present contribution focuses on the notion of mechanical texture, which is the pivot between mineral texture and DEM modeling.

2. Definition of mechanical texture

As stated above, assigning a mechanical texture to an ore implies that one identifies and ranks the textural features responsible for the physical fragmentation behavior of the texture of interest under stress, and the variability thereof. *The set of textural features that govern the mechanical behavior of the material of interest defines the mechanical texture of the material.* Textural features of interest may be associated with grain boundaries, pores, hard inclusions, shape, etc. This raises the question of how one may identify such textural properties in the first place.

The idea proposed here is to define some simple scheme for identifying such textural properties. When fracturing single particles by impact on a Hopkinson bar, one recognizes that individual particles behave differently from one another. The range of mechanical behavior of the particles is a direct measure of the variability of the mechanical texture of the material. We propose here that identification of mechanical texture components of significance relies on identifying those components which correlate most with the variability of mechanical behavior measured by sensitive equipment such as Hopkinson bars. Slow compression testing equipment could also be used to assess mechanical fracture properties of brittle particles, the rate of energy input being one decisive factor as to the choice of one method over the other.

This scheme first requires that one identifies the macroscopic fracture property which varies most significantly for a given lot of particles, its variability being taken as an indicator that the property in question best captures the intrinsic mechanical heterogeneity of the material of interest. This property is a macroscopic index for the mechanical texture of the ore. Identification of textural properties which comprise the mechanical texture of the material of interest will be those which correlate most with this macroscopic index.

In this section, we establish that *mass specific fracture energy*, noted *Ecs*, as measured by Hopkinson bar impact tests is a sound macroscopic index of mechanical heterogeneity. It is also interesting to note that *Ecs* has become a parameter of convergence for all current comminution models, which makes it likely that the concept of mechanical texture should eventually interface well with current comminution modeling schemes.

To derive this index, to which we shall eventually correlate the textural properties of the ore, the authors decided to test what may be considered a model material due to its extreme level of homogeneity from a mineral texture standpoint. Six millimeter soda lime glass beads underwent impact testing on a Hopkinson bar (Bourgeois and Banini, 2002).

Fig. 1 gives the force–time profiles measured by Hopkinson bar impact testing for the 6 mm soda lime glass beads. Tests were conducted using a 60 mm/882 g stainless steel ball bearing dropped from 80 mm. The clean superimposition of the force rise, which is expected given that the particles have the same shape, confirms the repeatability of the test protocol. What is significant here is the range of fracture forces measured for individual particles. This range spans from 2231 N to 4253 N, i.e. it varies by a factor of 2, which can be described satisfactorily using a Weibull distribution with parameters $k = 6.6$ and $\lambda = 3433$ N. The mass specific fracture energy *Ecs*, which is the energy actually absorbed by the particle before the point of fracture—not to be mistaken for the potential energy of the striker—varies by a factor of 4.5. The broad range of mass specific fracture energies reflects the significant variability of mechanical properties of the soda lime glass beads, despite their being a model material.

Force–time measurement from Hopkinson bar tests yields estimation of particle strength, stiffness and mass specific fracture energy (Bourgeois, 1993; Tavares and King, 1998). The former relates to the maximum load which the particle can sustain before fracturing, whereas the latter is associated to the amount of deformation of the loaded particle. Distributions of force at fracture and mass specific fracture energy measured for soda lime glass beads are shown in Fig. 2.

The distribution of fracture properties, which is revealed by the Hopkinson impact test carried out on individual particles, yields a good appreciation of how significant the distribution of mechanical properties is, even for a material seemingly as texturally homogeneous as soda lime glass. Tavares and King (1998) have shown that there is a strong correlation between particle strength and mass specific fracture energy for glass beads, but the issue here is not so much about the correlation between mean values, but more on the variability, i.e. the spread of the distribution of the measured properties.

The measured values of relative standard deviation (RSD) for mass specific fracture energy, strength and stiffness for the 6 mm soda lime glass beads were 0.39, 0.17 and 0.16 respectively.

Of the 3 properties which are readily available from Hopkinson bar impact tests, the mass specific fracture energy exhibits the largest variability. It is concluded that the mass specific fracture energy is a macroscopic

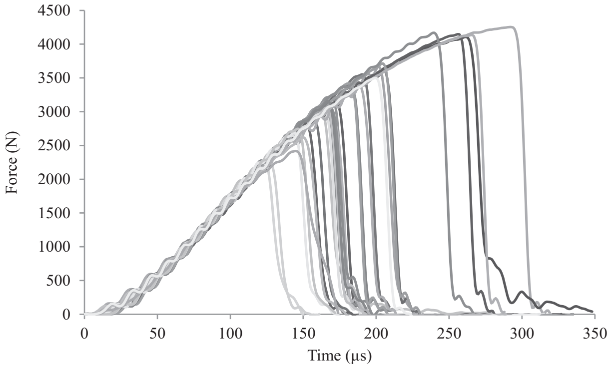

Fig. 1. Force–time profiles measured on 31 soda lime glass beads.