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Kinetic energy and its applications in mining engineering

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ABSTRACT

Reduction of energy consumption in comminution is of significant importance in mining industry. To reduce such energy consumption the energy efficiency in an individual operation such as blasting must be increased. By using both new investigations and previous experimental results, this paper demonstrates that (1) kinetic energy carried by moving fragments in rock fracture is notable and it increases with an increasing loading rate; (2) this kinetic energy can be well used in secondary fragmentation in crushing and blasting. Accordingly, part of the muck pile from previous blast should be left in front of new (bench) face in either open pit or underground blasting. If so, when new blast occurs, the fragments from the new blast will collide with the muck pile left from the previous blast, and the kinetic energy carried by the moving fragments will be partly used in their secondary fragmentation.

1. Introduction

The comminution of rocks consumes not only significant amounts of energy but also large quantities of steel due to wear of grinding media and machine liners. Comminution costs represent an important contribution, 30–50%, of total mining operation costs [1]. Therefore, reduction of the energy consumption in comminution is of significant importance in mining industry. To reduce such energy consumption, energy efficiency in comminution has to be increased, since in rock drilling, blasting, crushing, and grinding, the effective energy used in rock breakage is found to be quite small in comparison with the total input energy. In crushing and grinding, according to Prasher [2] the energy efficiency is of the order of 3% at the maximum. Chi et al. [3] have pointed out that, in fact, the energy introduced into comminution systems that actually results in the formation of a new fracture surface is usually less than 1%. Even in rock drilling it is estimated that only 10% of the input energy is used to fracture rock [4]. In rock blasting, energy efficiency has been reported by many investigators including Revnivtsev, Spathis, Ouchterlony et al. and Sanchidrian et al. [5–8]. Considering that the heat of explosion is the energy available in the blast, only 2–6% of it was used for fragmentation and 3–21% consumed as kinetic energy, according to the production blasts measured by Sanchidrian et al. [8]. In short, two conclusions can be made: (i) the energy efficiency in each of the above-mentioned operations such as drilling, blasting and grinding is very low, and (ii) the energy efficiency in one operation is quite different from that in other. For example, the efficiency in blasting is much higher than that in grinding. These two conclusions reveal two ways toward reducing the energy consumption [9]: (1) to change energy distribution among different operations so as to reduce total energy expenditure; (2) to increase energy efficiency in each individual operation.

Regarding the first way, various studies have been performed detailing how to improve rock fragmentation by decreasing the total energy expenditure [10–18]. The main idea in these studies is to enhance rock fracture in blasting so as to save more energy in the down-stream operations such as crushing and grinding.

Concerning the second way, different measures have been taken to increase the energy efficiency in blasting. These measures include: (1) to change stress or energy distribution by choosing a proper explosive whose VOD (velocity of detonation) well matches the sonic velocity of rock mass (e.g. [9]); (2) to achieve an effective stress superposition from neighbouring holes by using an appropriate delay time between holes (e.g. [19–20]); (3) to increase the amplitude of stress waves and to change the stress distribution by placing two primers with same delay time at different positions in a hole to obtain shock wave collision [21]; (4) to reduce or avoid detonation energy wastage from the collars by proper stemming or by correct primer placement [22]; and (5) to make the kinetic energy of a flying fragment used to break it again. On the last measure, as early as in 1962, Bergstrom and Sollenberger [23] found that during slow compression to single glass spheres, the fragments of the spheres flew away and they could carry up to 45%

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of the input energy. This finding indicates that if the kinetic energy carried by flying fragments can be utilized in further fragmentation, the energy efficiency in rock fragmentation will be largely increased. Then in different experiments it was found that higher loading rates were less efficient in rock fracture and fragmentation [24–27]. These investigations imply that the kinetic energy during rock fracture might be one of important reasons for the lower energy efficiency under high loading rates. If this is the case, a more important issue is how to increase the energy efficiency in rock fragmentation such as mechanical crushing and fragmentation by blasting. A common phenomenon has been observed in rock blasting: the first row in an open pit blast always produces more boulders than subsequent rows, see Refs. [28–30]. Even in small-scale laboratory experiments, it was found that the fragments from the first row are coarser than those from the second row [31]. In underground mining such as sublevel caving, an argument on how the production blasts should be performed immediately beneath hanging walls is still on-going. These questions need a theoretical study on the effect of kinetic energy on rock fragmentation, especially under dynamic loading conditions.

On the above background and by means of previous experimental results and new investigations, this paper will describe how kinetic energy is carried by fragments in either mechanical crushing or rock blasting, and discuss how to use this energy so as to increase the energy efficiency in fragmentation as well as comminution.

2. Experimental observations of secondary fragmentation

2.1. Kinetic energy in rock fracture

2.1.1. Energy partitioning in the SHPB system

Fracture of solids is a dynamic event, regardless of either static or dynamic loading. For example, rock bursts might be induced not only by dynamic loading but also by static loading [32–34]; during the slow compression tests that can be considered as a static or quasi-static loading condition, Bergstrom and Sollenberger [23] observed flying fragments. In a general case, when rock fracture occurs, various forms of energy are consumed. In rock blasting, the energy partitioning has been investigated by Hinzen, Spathis, Ouchterlony et al. and Sanchidrián et al. [6–8,35]. In order to illustrate energy partitioning easily, let us take the fracture of a rock sample in a Split Hopkinson Pressure Bar (SHPB) system as an example. The SHPB system is shown in Fig. 1. The impact bar applies total energy into the system by striking the incident bar. The energy applied to the incident bar is called incident energy W_I that consists of two equal parts: strain energy W_{IS} and kinetic energy W_{IK}. The strain energy can be determined by measuring the incident strain wave in the incident bar. Since $W_{IS} = W_{IK}$ in elastic waves [9], the incident energy W_I can be determined by only measuring W_{IS}, i.e.,

$$W_I = 2W_{IS} = 2\int_0^T \frac{1}{2}\sigma_I(t)\varepsilon_I(t)Ac_L dt = \int_0^T EAc_L\varepsilon_I^2(t)dt \qquad (1)$$

where E, A and c_L are the Young's modulus, cross-section area and sound velocity of the incident bar, respectively. $\sigma_I(t)$ and $\varepsilon_I(t)$ are the stress and strain at a certain point (section) of the incident bar, respectively. T is the wave length in time. Similarly, the reflected energy W_R and transmitted energy W_T can be determined. The incident energy and reflected energy can be determined by the strain waves measured from the strain gauges on the incident bar, and the transmitted energy determined from the gauges on the transmitted bar. The difference between $W_I - W_R$ and W_T is the energy that is absorbed and consumed by the rock sample [25]. This energy is expressed by W_L in the following.

$$W_L = (W_I - W_R) - W_T \qquad (2)$$

The energy W_L consists of several parts, as follows:

(1) Surface fracture energy of the main crack that completely separates the rock sample. In the case shown in Fig. 1, this energy is used to separate the sample into two pieces.
(2) Internal cracking and damage energy of the fragments produced in the fracture process. The branching cracks (or bifurcation) shown in Fig. 2 are typical internal cracking and damage. Such branching cracks increase with increasing loading rates in the dynamic fracture tests [25].
(3) Kinetic energy carried by flying fragments that was observed, for example, by Zhang et al. [36] during the dynamic rock fracture.
(4) Rotation energy carried by rotating fragments.
(5) Heat energy consumed in heating rock, for example in the tips of cracks.
(6) Electromagnetic radiation energy emitted during the fracture of some rocks. For example, electromagnetic radiation was found in rock bursts and earthquakes [37].
(7) Sound energy used in releasing sound.
(8) Other energies such as the energy consumed by friction. In the SHPB system, the contact between the rock sample and the bars consumes certain energy due to friction.

Note that in the above description, the energy analysis involves a whole process starting at the beginning of the striker bar's impact and ending at the time when the impact is completed and both the reflected wave and the transmitted one are completely recorded. In other words, the reflected waves from both the left end of the incident bar and the right end of the transmitted bar are not considered in the analysis. Note also that the transmitted energy in the SHPB system corresponds to the seismic or vibration energy as well as some other forms of energy in rock engineering.

2.1.2. Kinetic energy measured during rock fracture in SHPB system

The measurements [25] show that the kinetic energy W_{KE} increases with the speed υ_o of the striker bar, and the relation between the ratio W_{KE}/W_L and the υ_o is

$$W_{KE}/W_L = (0.69\upsilon_0 + 0.22)/100 \qquad (3)$$

This equation indicates that the ratio W_{KE}/W_L increases with υ_o. As the impact speed υ_o is 9.6 m/s (measured in the test), the result is $W_{KE}/W_L = 7\%$. It is assumed that Eq. (3) is valid when $\upsilon_o \geqslant 10$ m/s, then the result becomes $W_{KE}/W_L = 14\%$ and 28% if υ_o = 20 m/s and 40 m/s, respectively. Note that in the SHPB system,

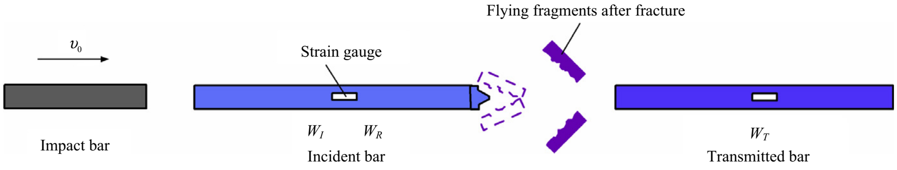

Fig. 1. Energy partitioning in SHPB system.