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Liberation of various types of composite materials by controlled underwater explosion

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ABSTRACT

Controlled underwater explosions of various composite materials (i.e. discarded DVDs, end-of-life mobile phones, tungsten carbide scrap as well as concrete slabs) were carried out in order to indicate the potential of this novel technique in liberating valuable components for recycling. The great advantage of the underwater explosion is especially noticeable where excessive comminution needs to be avoided in order to increase the degree of liberation or reduce the size of hazardous or composite materials. The main finding of this work is that a controlled underwater explosion, a contactless method, ensured the liberation of valuable components from the mounting matrix by generating enough pressure in solids during the transfer of the pulse through the medium (i.e. water). In other words, high-pressure pulses induced the liberation of valuable components that have a boundary with less valuable matrix.

1. Introduction

Breakage is the first and most important step of a process series occurring in a plant, prior to sorting, recovering or upgrading different components from each other (King, 1979; Russo et al., 2004; Kim et al., 2012). The aim is to produce particles that consist of only of the component of interest, which are usually called "liberated particles" (Heiskanen, 1993; Wills, 1997; King, 2001; Gay, 2004). According to Klimpel and Austin (1983), the term "liberation" is loosely used to indicate that the breakage or the size-reduction process will produce some particles, which are so enriched in the valuable component (i.e. free particles) that they can be separated from other particles containing less of the same valuable component, thus leading to a pure fraction. Clearly, the degree of liberation, which indicates the degree to which a given component is detached from other components that are regarded as contaminants, depends primarily on the size-reduction process, since each process will produce different sizes and amounts of valuable component in different manners (Barbery, 1992).

Broadly speaking, the degree of liberation of the valuable component "A" from a composite material "A–B" increases as particle size is reduced. Gaudin (1939) described the degree of liberation as the percentage of a component "A" occurring as "free particles" (i.e. particles consisting of a single component), in relation to the total of that component occurring in all particles. Of course, depending on the size-reduction technique being used, the number of such completely free or liberated particles may be limited, and there will be many other particles containing mixtures of "A" and "B" in various proportions (Barbery, 1992).

The degree of liberation L_a is defined as the percentage of particles or pieces that are formed wholly of the valuable component within a size fraction of particles that contains that particular valuable component (Berube and Marchand, 1984; Ferrara et al., 1989; Barbery, 1992; Bole et al., 1993; Stamboliadis, 2008).

$$L_a = \frac{\text{Mass of particles that consist of ONLY the valuable component}}{\text{Mass of particles that contain the valuable component}} \times 100 \quad (1)$$

The grade G_v of a product, on the other hand, is defined as the percent in valuable component within the composite material:

$$G_v = \frac{\text{Mass of the valuable component}}{\text{Mass of the composite material}} \times 100 \quad (2)$$

The degree of liberation is therefore a measure of the valuable component "A" that is free or liberated from all other components, without regard to distribution of grade for that matter (Berube and Marchand, 1984; Miller and Lin, 1988; Zhang and Subasinghe, 2013).

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Several authors, including Berube and Marchand, 1984; Lin et al., 1987a, 1987b; Austin and Luckie, 1988; Laslett et al., 1990; Bonifazi and Massacci, 1995; Leigh et al., 1996; Fandrich et al., 2007; Schena et al., 2007; Vizcarra et al., 2010 have reported that the degree of liberation of valuable components or phases from a host composite material is usually quantified by visual or optical examination of valuable component embedded in a mounting matrix by means of a optical microscope, X-ray computed tomography (CT).

The two most important fundamental properties that describe the liberation are the size of the "resulting" particles and their materials composition, which are both manipulated by a size-reduction process (Heiskanen, 1993; King, 2001). As early as 1939, Gaudin (1939), a researcher in the field of mineral processing, had pointed out that in order to increase the degree of liberation, composites need to be broken as fine as necessary, down to the size of particles to be "liberated". In other words, the efficiency of the separation process is very much dependent on the degree of liberation of valuable components in a composite, which must be sufficiently ground or reduced in size to permit the production of sufficiently high grade fraction.

Nowadays, most of the end-of-life or waste materials undergo random size-reduction, also known as comminution, on their way to final processing, use or destination. The main objective of comminution in the form of cutting, shredding, crushing or grinding is to liberate valuable components from other less valuable components.

It has been reported that the specific energy consumption of comminution varies from a few kW h/t for crushing, to over 100 kW h/t for ultra-fine grinding (Wang et al., 2011). Hence, by decreasing the particle size, the energy consumption substantially increases. This high degree of energy consumption implies both high operational cost and greenhouse footprint (Gay, 2004).

A product exiting the conventional comminution process is generally not sufficiently liberated or is over-ground, indicating that this mechanical process is not an ideal liberation technology; rather, it is a technology of reducing the dimensions of the material, with liberation occurring more as a secondary outcome. Conventional comminution technologies are therefore sometime inefficient in promoting liberation of valuable components, and excessive size-reduction or over-grinding must be avoided in order to reduce the electricity consumption in particular (King, 1979; Veasey and Wills, 1991; Schubert and Bernotat, 2004).

In order to avoid an excessive size-reduction, the inter-granular breakage along the grain boundaries would be desirable, since it would allow keeping the natural grain size and minimizing the over-grinding. A major challenge remains, therefore, in the developing techniques which can effectively use the input energy to promote liberation by boundary fracture of the valuable components, preventing unnecessary size-reduction of the feed (Veasey and Wills, 1991). This enhanced liberation would be of benefit because it would be achieved without needing to grind particles to fine sizes, which in turn would reduce the energy consumption. In addition, over-grinding produces fine particles that tend to interfere with the subsequent separation process, making the downstream processing less efficient.

Broadly speaking, conventional comminution techniques, which are usually used for liberation, are not suitable for processing hard (Mohs hardness >9; such as tungsten carbide) or hazardous (such as spent lithium-ion batteries) materials. Several unconventional comminution methods such as: high-pressure waterjets (Kuyumcu and Rolf, 2004), sonic impulses (Linß and Mueller, 2004; Wilson et al., 2006, 2007), microwaves treatment (Kingman et al., 2000), and electro-hydraulic disintegration (Yutkin, 1955; Andres, 1977; Ito et al., 2009; Dodbiba et al., 2012) to name a few, have therefore been reported. In this study, a novel liberation technique by means of a controlled underwater explosion is put forward. The shock wave generated by explosion can cause extremely high pressure and therefore can break composites or hard materials. This paper illustrates how the controlled underwater explosion can be applied prior to sorting, separation or extraction of valuable components from composite materials.

2. Principle of underwater explosion

A so-called "explosive process" was first introduced in the mid-sixties by Snyder (1966), who pressurized rock lumps with hot gases followed by a fast drop (within 0.01 s) of pressure down to atmospheric level. Initiated by this drop of pressure, the lumps exploded and disintegrated. Nowadays, the main utilization of explosive is in large-scale public works such as: dam construction, land development, mining, demolition of buildings, etc.

The technological benefit of the controlled underwater explosion is that it can explode or disintegrate complex composite materials without the introduction of the explosive inside the sample (Fujita et al., 2008). The mechanism of disintegration or mechanical fragmentation of solid by high-pressure pulses is a direct result of explosion. The authors also believe that other advantages of the underwater explosion when compared with conventional comminution methods are that it can: (1) crush or reduce the size of hard materials (e.g.: tungsten carbide scrap; reinforced concrete slabs, etc.); (2) "detach" or "disjoint" materials of different densities without excessive crushing or grinding (e.g.: electronic waste; demolition waste, particularly reinforced concrete slabs, etc.); (3) dismantle or reduce the size of materials/devices which processing can emit hazardous gases (e.g.: crushing of spent lithium-ion battery can produce HF gas).

It is well known that explosion is a chemical reaction that converts an explosive material into a gas at very high pressure, generally in the order of 50,000 atm (Cole, 1948). The energy E_s (in J/m^2) of the shock waves given as (Kanel et al., 2004; Rajendran and Narasimhan, 2006; Rajendran, 2008; Andreopoulos, 2013):

$$E_s = \frac{1}{\rho c}\int_0^t p^2(t)dt \tag{3}$$

where ρ (in kg/m^3) is the density of water, t (in s) is the time, and c (in m/s) is the velocity of sound in water medium. The shock pulse c (in MPa), on the other hand, which has an instantaneous rise and an exponential fall, is given by the following equation:

$$p = P_m e^{-t/q} \tag{4}$$

where q (in μs) is a time constant, and P_m (in MPa) is the instantaneous peak pressure, which is given as (Rajendran et al., 2007):

$$P_m = 52.16\left(\frac{W^{1/3}}{S}\right)^{1.13} \tag{5}$$

where W (in kg) is the quantity of the explosive charge, and S (in m) is the stand-off distance (i.e. the distance between the explosive and the composite). In addition, the time t that can be calculated by using Eq.(6) (Rajendran et al., 2007).

$$t = 96.5(W^{1/3})\left(\frac{W^{1/3}}{S}\right)^{-0.22} \tag{6}$$

It is worth noting that the underwater explosion generates bubbles containing hot gaseous products of the explosion as well as a shock wave with high velocity and pressure propagating radially outwards. These in turn have a damaging effect on the adjacent solid structure or composite material (Zhang et al., 2008). After the explosion, the pressure of shock wave in water rapidly reaches a peak and then drops exponentially. Similarly, the size of gas