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The Influence of Different Mineral Processing Techniques on the Bio-extraction of Metal Values from Ores and Secondary Sources

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CONTENTS

RESUMO

A progressão do processo de lixiviação pode bem ser descrita por um processo de reação-difusão combinado que progride através da rede de fissuras e poros, mais próximos da superfície das partículas, causadas por diferentes técnicas de processamento mineral, tais como britagem com britador de mandíbulas, HPGR (*High pressure grinding rolls* - rolos de moagem de alta pressão) e fragmentação eletrodinâmica, cada uma delas com suas próprias particularidades. A extensão e a profundidade desta rede de fissuras são função do tamanho das partículas e do método de cominuição. O desafio é definir um modelo de taxa de lixiviação simplificada de modo a descrever a extensão da lixiviação, ao longo do tempo, em termos de um conjunto de parâmetros que podem estar relacionados apenas com o tamanho de partícula e o modo de britagem. A bio-extração de metais a partir de minérios, mais precisamente o processo de biolixiviação, é um processo hidrometalúrgico mediado pela ação de micro-organismos indógenos que necessitam de nutrientes (*i.e.*, N, P e K) para seus metabolismos e dióxido de carbono como a única fonte de carbono, contido no ar utilizado, para geração de biomassa. O processo de biolixiviação de minérios em uma pilha leva em consideração uma faixa própria de tamanho de partícula de modo a alcançar uma eficiência de extração tão elevada quanto possível durante o período de lixiviação.

Palavras-chave

HPGR, Fragmentação eletrodinâmica, biolixiviação, minério e fontes secundárias.

ABSTRACT

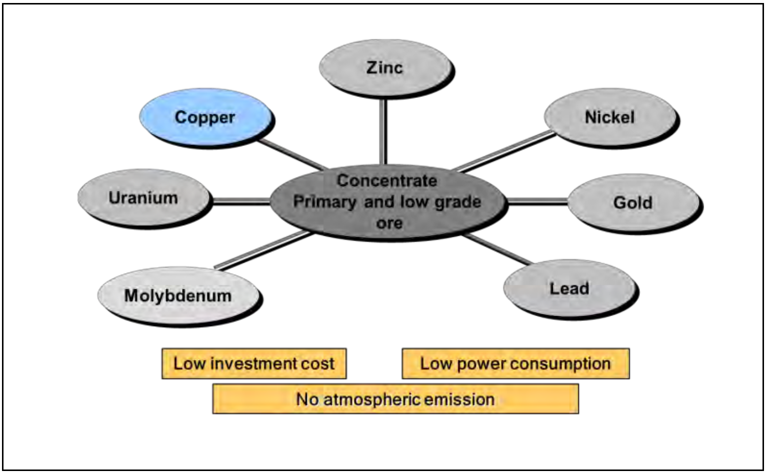
The progression of the leaching process can rather be described by a combined reaction–diffusion process progressing through the network of cracks and pores closer to the particle surface caused by those different ore processing techniques, such as jaw crushing, HPGR (High pressure grinding rolls) and electrodynamic fragmentation, each one of them with their own particularities. The extent and depth of this cracking network are a function of particle size and comminution method. The challenge is to define a simplified leaching rate model so as to describe the extent of leaching over time in terms of a set of parameters that can all be related to just particle size and crushing mode. The bio-extraction of metals from ores, more precisely the bioleaching process, is a hydrometallurgical process mediated by indigenous microorganisms that need nutrients (*i.e.*, N, P and K) for their metabolisms and carbon dioxide as the only source of carbon, from the air, for generating biomass. The bioleaching process of ore in a heap takes into consideration a particular particle size range so as to reach as high extraction efficiency as possible over the leaching period.

Keywords

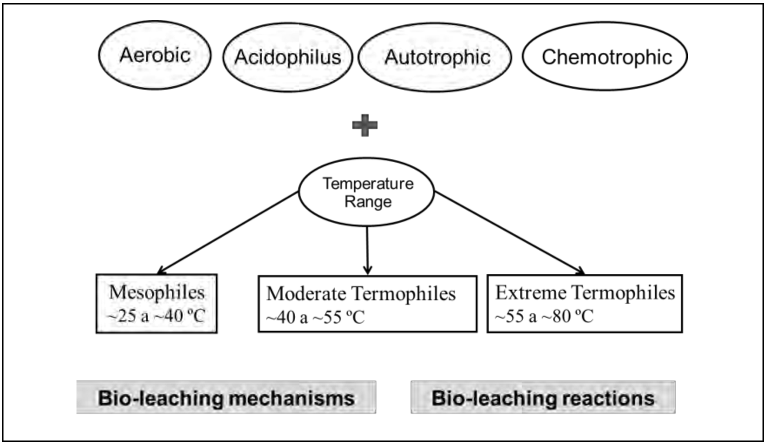
HPGR, electrodynamic fragmentation, bioleaching, ore and secondary sources.

1 | INTRODUCTION

The bioleaching is a biotechnological process based in the use of microorganisms capable to solubilise metals through the oxidation of sulphide minerals.



Microorganisms features



Main reactions

Pyrite

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$$

$$2FeSO_4 + 0{,}5O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$$

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$$

$$FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S^0$$

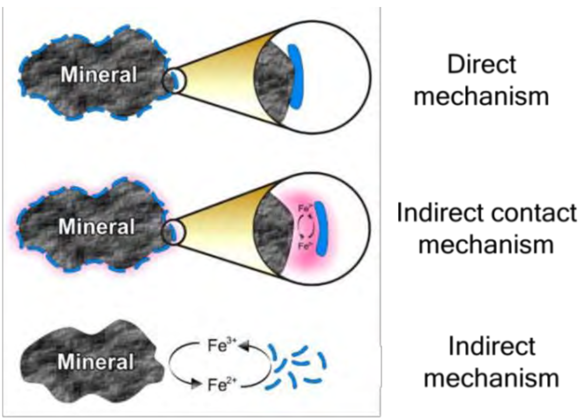
Chalcopyrite

$$2CuFeS_2 + 8{,}5O_2 + H_2SO_4 \rightarrow 2CuSO_4 + Fe_2(SO_4)_3 + H_2O$$

$$2FeSO_4 + 0{,}5O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$$

$$CuFeS_2 + 2Fe_2(SO_4)_3 \rightarrow CuSO_4 + 5FeSO_4 + 2S^0$$

$$2S^o + 3O_2 + 2H_2O \xrightarrow{microorganism} 2H_2SO_4$$



Mechanisms by which microorganisms might interact with a sulphide mineral. Source: Oliveira (2009)

Most heap bioleaching models, regardless of whether they deal with leaching at the particle scale or focus on bulk scale phenomena, such as liquid flow, gas flow, and temperature distribution, account for the effect of particle topology by using simplified models such as the shrinking core concept applied to an average particle size or a generic size distribution.

In addition to all that were mentioned about the use of mineral processing techniques for extracting metal values from ores, they are likewise promising for recovering metal values from secondary sources, electrodynamic fragmentation in particular, such as scraps from the electro-electronic industries (*i.e.*, obsolete computers, electro-electronic devices, plated pieces etc.).

The availability of high grade ores is decreasing in the world. Moreover, the mining industry has suffered with the rise on energy cost and the growing environmental constraints. Therefore, there has been a growing interest to search and develop more efficient and sustainable processes, such as the ones capable to exploit low grade mineral resources and tailings. In this context, heap bioleaching is gaining importance as a low cost technology for processing low grade ores. It is currently used for extracting base metals such as copper, nickel, cobalt etc., and precious metals such as gold and silver. In fact, bioleaching constitutes an alternative process to roasting, smelting and pressure leaching, avoiding their high energy consumption, with less pollution and safety risks. Furthermore, bioleaching is generally employed for processing large particles and aggregates. Despite its energy efficiency, this fact leads to a limitation as only grains at the surface of particles are exposed to the leach solution.

2 | TECHNICAL CONSIDERATION

In the last years, the application of microbiological methods to the extraction of metals from minerals has definitely gained a prominent role supported by the several bioleaching and biooxidation processes operating in different sites over the world. This may be an important reason why fundamental research has received a new powerful stimulus with fascinating discoveries and in addition it surely will become the cause of future development in the field.

Bioleaching is the biological conversion of an insoluble metal compound into a water soluble form. In case of metal sulphide bioleaching, metal sulphides are oxidized to metal ions and sulphate by aerobic, acidophilic Fe(II) and/or sulphur compound oxidizing Bacteria or *Archaea*. Bioleaching involves chemical and biological reactions. Despite molecular oxygen being the final electron acceptor for the overall metal sulphide bioleaching process, Fe(III) ions are the relevant oxidizing agent for the metal sulphides. The metal sulphide oxidation itself is a chemical process in which Fe(III) ions are reduced to Fe(II) ions and most of the metal sulphide is oxidized to sulphate, and various intermediate sulphur compounds, such as elemental sulphur, polysulphide, thiosulphate, and polythionates. For example the oxidation of sphalerite (ZnS) to elemental sulphur is given in the following equation:

$$ZnS + 3Fe^{3+} \rightarrow Zn^{2+} + 0{,}125S_8 + 2Fe^{2+} \quad [1]$$

The role of the microorganisms in the bioleaching process is to oxidize the products of the chemical metal sulphide oxidation (Fe(II) ions and sulphur- compounds) in order to provide Fe(III) and protons, the metal sulphide attacking agents. In addition, proton production keeps the pH low and thus, the Ferric ions in solution.

Aerobic, acidophilic Fe(II) oxidizing Bacteria or *Archaea* provide Fe(III) by the following equation:

$$2Fe^{2+} + 0,5O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \quad [2]$$

The aerobic, acidophilic sulphur-compound oxidizing Bacteria or *Archaea* oxidize intermediate sulphur compounds to sulphate and protons (sulphuric acid). Most relevant is the oxidation of elemental sulphur to sulphuric acid since elemental sulphur can only be biologically oxidized under bioleaching conditions:

$$0,125S_8 + 1,5O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+ \quad [3]$$

The sulphur-compound oxidizing Bacteria or *Archaea* produce protons which dissolve metal sulphides besides pyrite, which is not acid-soluble. Pyrite is only attacked by Fe(III) ions (not by protons) and, therefore, only dissolved by Fe(II) oxidizing Bacteria or *Archaea*. The Figure 1 shows how the bioleaching of a metal sulphide bearing ore takes place.

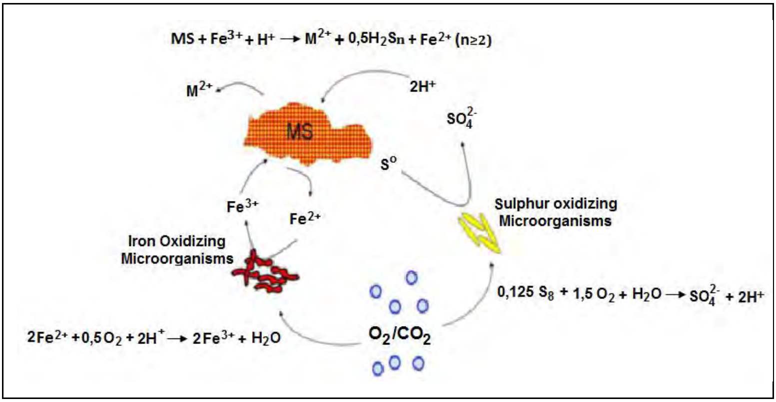


Figure 1. The schematic representation of bioleaching mechanism (Adapted of Hansford and Vargas, 2001).

Although heap leaching is by now a well-established technology choice in the mining industry, the process remains limited by low recoveries and long extraction times. It is becoming increasingly clear that the successful application of heap leaching technology will ultimately depend on having a comprehensive understanding of the underlying fundamental processes for optimisation to take place. Ores are placed in heaps in a relatively coarse particle size distribution, reaching up to 25 mm top size for crushed and agglomerated ores and as much as 500 mm for ROM ores in dump leaching. Leaching from such large particles is poorly understood and commonly assumed to follow shrinking core type behaviour. However, a comprehensive literature review has returned virtually no evidence to support this assumption, nor is there much of an understanding how exactly minerals leach from any solid matrix.

The subject of this plenary talk is, therefore, to give a quick flavour on how the diffusion reaction phenomena of reagents through large particles takes place and to provide true and reliable physical parameters to formulate the relevant modelling approaches to large particle leaching. A combination of standard optical microscopy, SEM, QEMSCAN and X-ray CT techniques has been used for the characterization of crack networks and mineral dissemination in the ore particles, which are important characteristics that determine the diffusion of reagents into and out of particles and the reactions within.

The present work aimed at investigating the effect of different crushing methods in the generation of cracks in large particles of base and precious metals ores in order to enhance the exposure the minerals of interest. The increasing of surface exposure can potentially enhance bioleaching rates. The challenge is the microstructural characterization of samples composed by macroscopic particles, *i.e.,* particles in the order of 1 mm or more in a resolution better than 1 μm in which thin cracks can be analyzed.

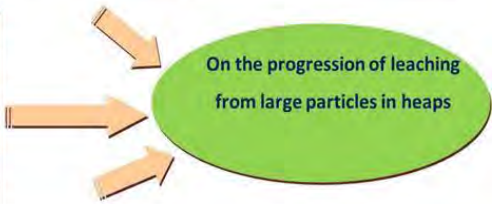
Heap bioleaching is gaining importance as a low cost technology for processing low grade ores and tailings. Furthermore, it can be employed to process large particles and aggregates. Nevertheless, only grains at the surface are exposed to the leaching solution. The present work aims at investigating the effect of different crushing methods in the generation of cracks in order to improve the surface exposure of metal sulphides. A method for the microstructural characterization of samples composed by macroscopic particles, *i.e.,* around 1 mm or more in a resolution better than 1 μm, is employed. This method involves large cross-sections preparation, image acquisition on SEM, automatic mosaicing, and image processing and analysis. The results show that it is possible to increase the copper sulphide minerals exposure through the generation of cracks by secondary crushing for a given particle size range.

Comparative comminution between high voltage pulses and conventional grinding, at the same specific energy levels, shows that the electrical comminution generates a coarser product with significantly less fines than the mechanical breakage. However, minerals of interest in the electrical comminution product are better liberated than in the conventional comminution with an over 95% statistical significance. There is a potential to use less energy in the electrical comminution to generate the similar degree of mineral liberation as in the mechanical comminution. Distribution of the liberated minerals demonstrates that, in the electrical comminution product, a large percentage of the liberated minerals appear in size fractions coarser than 53 μm; while in the mechanical comminution product, the liberated minerals are accumulated in fine and very fine size fractions. Therefore there may be potential benefits in recovering the coarse liberated minerals in the electrical comminution product, prior to further grinding.

Since the chemical/biochemical leaching of the ore samples and investigation of the effective parameters are extremely diverse, the scope and boundaries of such study can be seen in (Figure 2). This research shows the leaching behaviour at the surface and in the interior of large particles (from 5 to 25 mm). Chemical leaching and bioleaching are considered for a typical sulfide ore at ambient temperature.

Physical and chemical characterization		
Key characteristic mapped in 3D	**Ore Type**	**Mineralogy and surface properties**
Tomography of cracks, voids and micro-structure	Sulfide ores	Mineral composition and dissemination
Grain distribution	Oxide ores	Particle Size distribution (5 to 25 mm)
Free surface		Acid consumption
Liberation		Formation of precipitates
Mineralogical association	Carbonate	Galvanic interactions
Mechanical imperfections on particle surface		
Particle shape		
Evolvement of permeability of ore granular media		Hydrophobicity

Comminution
Principal breakage mechanisms
Impact
Compression
Abrasion
Attrition



Chemical/biochemical leaching			
Microorganisms	**pH**	**Temperature**	**Chemical Reagent**
Mesophiles	Acidic	Ambient temperatures (below 40°C)	Sulphuric acid
Moderate thermopiles	Alkali	Between 45 - 60 °C	
Thermopiles		60- 80°C	
Extreme thermopiles		greater than 80 °C	
Abiotic			

Figure 2. Area shaded in orange colour highlights the key components for the ore physical and chemical characterization (Yousef Ghorbani – Thesis at University of Cape Town, 2012).

With the typical ore grades declining and the economic and environmental cost of energy increasing, less energy intensive metal extraction techniques are becoming more attractive. One of these methods is heap leaching, which from its first implementation for the recovery of gold from low-grade ores by cyanidation in the early 1970s, has, in conjunction with solvent extraction and electrowinning, developed into a key hydrometallurgical technology for the recovery of base metals, primarily copper from both oxides and secondary sulfides.

Heap and dump leaching offer a number of advantages embracing simple equipment, low investment and operation cost, and reasonable yields over a period of recirculation. In the immediate future, heap leaching is likely to be a major area of expansion. In the United States, approximately one-third of gold and nearly 30% of total new copper production come from heap leaching. Nearly all new copper and gold mines involve some ore processing by heap leaching. Although heap leaching for zinc and uranium has been considered before, it is gaining renewed attention. Despite the current widespread use of heap leaching in industry, the process is still limited by low recoveries, long extraction times, and high operation costs, especially in terms of acid consumption and at its core, this relates to a limited fundamental understanding of the process. This knowledge is derived from the investigation of the interactions between the physical, chemical and biological processes that drive a heap (Acevedo, 2002; Dreisinger, 2006; Mellado *et al*., 2009).

Heap leaching from low-grade ores has become a major contributor to the total global extraction of economically important metals, notably copper, gold, silver, and uranium (Padilla *et al*., 2008). Although the concept of heap bioleaching appears to be very simple, the sub-processes taking place within the heap are rather complex, and their interactions are not yet fully understood. Dixon and Petersen (2003) distinguish between different processes ranging from the macro- to the grain-scale, as is illustrated in Figure 3. At the macro scale, kinetics is governed primarily by transport of mass and energy into, through and out of the heap structure.

At the aggregate scale, gas uptake into the liquid phase, intra- and inter-particle diffusion within the stagnant zones, and bacterial growth and oxidation are all contributing to the leaching kinetics. Aggregate scale processes at the 'meso'-scale occur at the level of a cluster of ore particles. The important processes at this level are oxygen uptake into solution from the air space, diffusion of dissolved chemical species through the inter-particle pores, and microbial processes.

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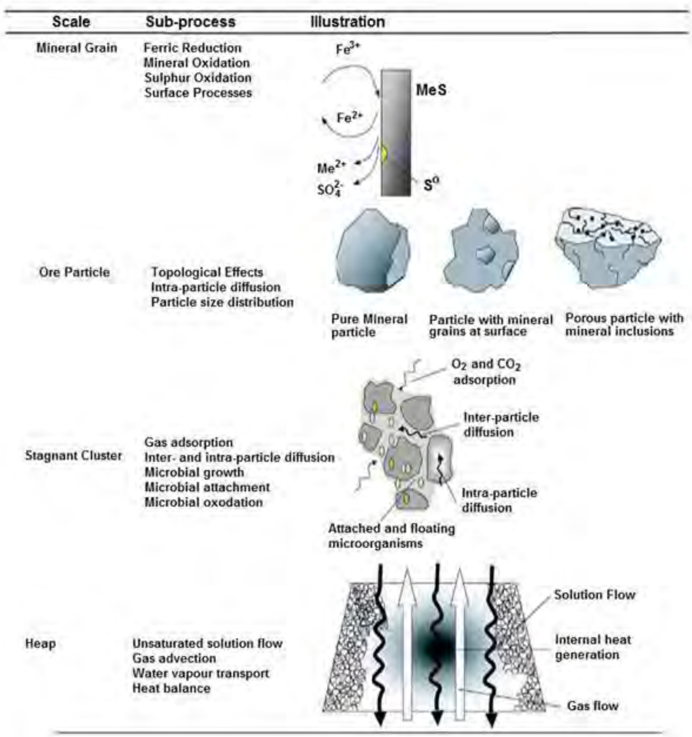

Figure 3. Schematic representation of sub-processes in heap bioleaching (Adapted of Dixon and Petersen, 2003).

HPGR and Electrodynamic Fragmentation

a) HPGR – High pressure grinding roles

The basic machine concept and operation is relatively simple. The material is force-fed into the unit by creating a head of material over the machine, as seen in Figure 4. Two counter-rotating rolls allow the compression breakage to be used in a continuous rather than batch operation.

One of the rollers in the HPGR rotates on a fixed axis while the other is allowed to move linearly with a pressing force applied to the moving roll. The moveable roller is forced up against the material in the gap between the rollers by a hydraulic oil pressure system.

In the HPGR, the grinding force is transferred from one particle to the next, with a small proportion of the particles coming into direct contact with the rolls.

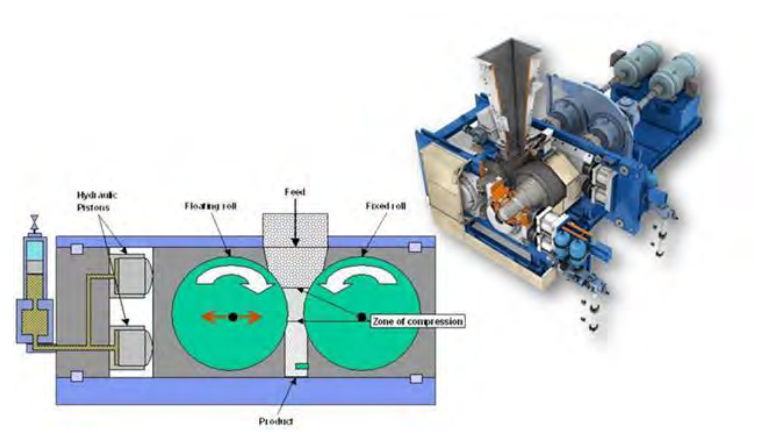

Figure 4. The main components of a Polysius HPGR.

The Figure 5 shows a comparison between an ore particle processed using a jaw crusher, HPGR and a cone crusher highlighting the micro-cracks generate while using such equipment.

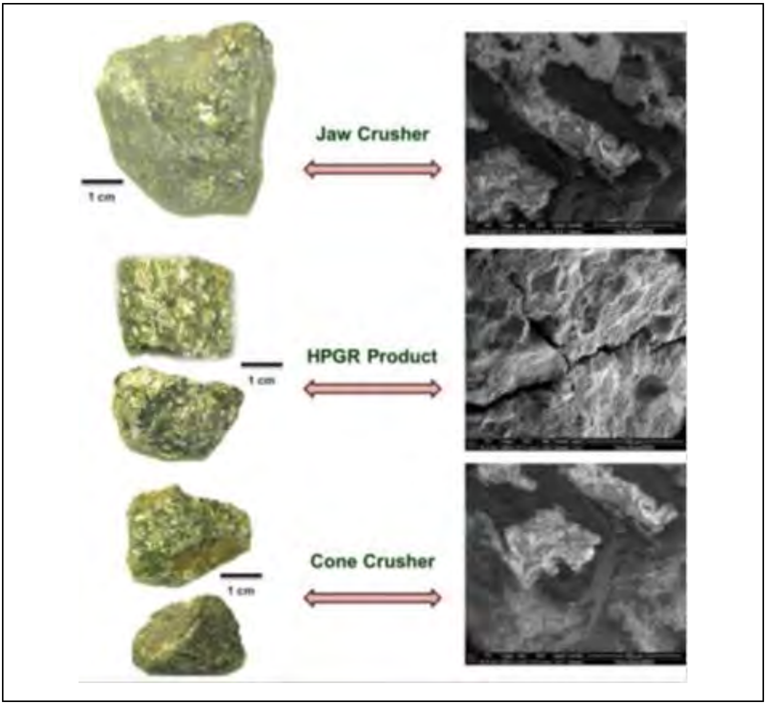

Figure 5. Standard optical photomicrograph and SEM photographs of five ore particles compared by different comminution methods (jaw crusher, cone crusher and HPGR). Note the presence of the micro-cracks in the particle prepared by HPGR.

b) Electrodynamic fragmentation

This technique takes into consideration, while processing ores, which is composed by a mixture of different minerals, that each material react differentially to an electrical stimulation (high voltage pulse), as they have different dielectric constants. It is based on a HV physical specificity, and at short pulse rise time (t) water isolates more than solids; finally, the discharge occurs through solid, causing strong internal shockwaves resulting in selective breakage. The Figure 6 shows, schematically, how that fragmentation takes place.

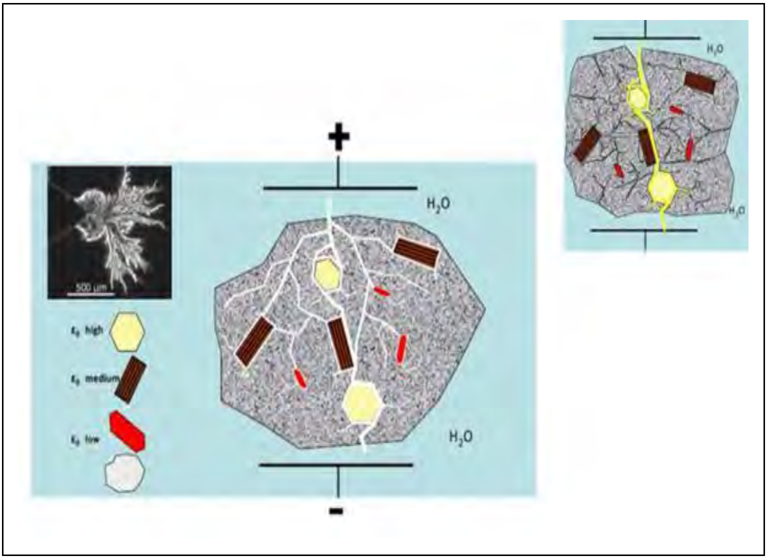

Figura 6. Selfrag- Electro-dynamic Fragmentation www.selfrag.com.

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3 | CONCLUSIONS

- The use HPGR for processing ore before bioleaching metal sulphide bearing ores can potentially enhance the metal extraction, but as the bioleaching goes on can bring the fines problem during percolation further.
- The effect of electro-dynamic fragmentation (Selfrag) and HPGR as secondary crushing methods in the generation of cracks in large particles of a copper ore was investigated.
- The results have shown that it is possible to increase the exposure of sulphide minerals grains by generating cracks through a secondary crushing. However, for ore processing purposes, other factors must be considered such as the generation of ore fines, and the energy consumption in the crushing operations.

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