



Electrochemical bioleaching of high grade chalcopyrite flotation concentrates in a stirred bioreactor

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ABSTRACT

The main objective of this study is to improve the basic understanding of electrochemical bioleaching as an advanced hydrometallurgical process suitable for the treatment of high grade complex sulfide ores and to use this understanding for analyzing the potential of this process for copper recovery from high grade chalcopyrite ores and flotation concentrates. Using a typical flotation concentrate from the Sarcheshmeh copper processing complex (located in the south-east of Iran) and mixed mesophilic as well as moderately thermophilic microorganisms, leaching experiments were performed in a stirred bioreactor. The emphasis was given on the comparison between the results of bioleaching and that of electrochemical bioleaching tests. From the results of this study, it can be pointed out that compared to the conventional bioleaching; the electrochemical bioleaching of chalcopyrite flotation concentrate leads to about 35% more copper recovery. It seems that the main reason for increasing copper recovery by electrochemical bioleaching is the control of redox potential between 400 and 425 mV. Under this condition, the precipitation of iron oxy-hydroxides on the surface of chalcopyrite, which can act as a diffusion barrier and prevents chalcopyrite dissolution, is significantly reduced. This leads to a higher electrochemical reduction of chalcopyrite and its improved dissolution.

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1. Introduction

Chalcopyrite is the most important copper-bearing mineral in the world. This mineral is known to be recalcitrant to hydrometallurgical processing. Much effort has been directed towards developing a hydrometallurgical process suitable for the treatment of high grade chalcopyrite ores with very limited success. It was believed that biohydrometallurgical techniques could offer one of the better alternatives for treatment of such ores. In the last three decades, microbial leaching operations have been developed into an emerging biotechnology. During this period, bioleaching has been applied successfully to the extraction of copper from low grade and secondary copper sulphides such as chalcocite and oxidation of refractory gold ores in both uncontrolled dumps and designed bioheaps. Also during this period of time, stirred tank bioleaching has been commercialized for cobalt recovery and for biooxidation of refractory gold concentrates. However, in the case of chalcopyrite ores and concentrates, biohydrometallurgy remains a promising technology (Olson et al., 2003; Watling, 2006; Ranjbar et al., 2007; Van-Aswegen et al., 2007).

Among the various microorganisms used in the bioleaching of metals, mixed thermophilic cultures have shown higher potential for copper recovery from chalcopyrite compared to mesophiles. In practice, moderate thermophilic microorganisms are being preferred, because they are more resistant to higher pulp densities and higher heavy metal concentrations than extreme thermophiles (Rodriguez et al., 2003; Olson and Clark, 2004; Cancho et al., 2007). The main hindrance to the commercial application of microbial processing of chalcopyrite concentrates is its low dissolution rate. (Watling, 2006; Pradhan et al., 2008). Several studies have shown that even in high acidic solutions, surface passivity of chalcopyrite at solution potential above a certain level, is the most important problem for dissolution of chalcopyrite (Hiroyoshi et al., 2001, 2008; Pinches et al., 2001; Third et al., 2002; Cordoba et al., 2008). The nature of this passive layer is not well known, but it is believed that a compact sulfur layer (Munoz et al., 1979; Dutrizac, 1989), a metal deficient chalcopyrite-like sulfide layer (Waren et al., 1982), a polysulfide like Cu_xS_y (Biegler and Horn, 1985) or an iron-bearing precipitate like jarosite (Stot et al., 2000) is responsible for passivity of chalcopyrite surface, which can lead to slow and incomplete extraction of copper. To overcome the problem, the formation of the passive layer must be prevented. One of the most discussed solution for this problem, is the possible control of pulp oxidation reduction potential (ORP) during the bioleaching process which can be achieved either electrochemically by applying a potential from an external source through a working

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electrode or chemically by the addition of reducing and oxidizing agents. The electrochemical reduction method has attracted more attention, because it avoids contamination of the solution and consumption of reducing/oxidizing agents (Fuentes-Aceituno et al., 2008).

Different studies have shown that applying negative potentials to the pulp significantly enhances the activity and growth of microorganisms and increases the dissolution rate of chalcopryrite (Natarajan, 1992; Nakasono et al., 1997). It was also observed that the formation of jarosite can be significantly reduced by passing current through the system, while the rate of chalcopryrite leaching increases slightly (Conner, 2005). Despite the important role of solution potential on chemical and biological reactions during bioleaching, to date, no essential attention has been paid to the electrochemical bioleaching as a promising technology for recovery of metals from complex sulfide ores like chalcopryrite. To identify the commercial application potential of this technology in Iranian copper industry, a research program was initiated. The objective of this program is to evaluate electrochemical bioleaching process for copper recovery from high grade chalcopryrite ores or flotation concentrates.

2. Materials and methods

2.1. Ore concentrate

A representative copper sulfide flotation concentrate, obtained from Sarcheshmeh Copper Mine (Kerman, Iran) was used in all experiments. X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses of the sample showed 27.73% Cu, 24.59% Fe, 14.82% S, 0.99% Zn and chalcopryrite (CuFeS_2) as the major mineral and pyrite (FeS_2) as the minor one together with small amounts of other sulfides and oxides. Table 1 presents the mineralogical composition of the sample. The particle size analysis of the sample by sieving and cyclosizer resulted to a d_{80} of about 75 μm .

2.2. Microorganisms

Two types of mixed cultures were used in the bioleaching tests. The first one contained strains of *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Leptospirillum ferrooxidans*. This culture was previously isolated from the Sarcheshmeh Copper Mine (Iran). The second culture consisted of moderately thermophilic, acidophilic iron and sulfur oxidizing bacteria and was originally obtained from the Mintek Company (South Africa). The cultures were routinely sub-cultured in a shaker incubator at the desired temperature of 35 °C or 50 °C and initial pH of 1.8 in a 9 k medium (Silverman and Lundgren, 1959).

2.3. Analytical techniques

The concentration of total iron and copper in the leach solutions were determined by atomic absorption spectroscopy (AAS, Varian 220). After each test, the solid residue was filtered, rinsed with distilled water, left to air dry and sent for analyzing by AAS and scanning electron microscopy (SEM) equipped with an energy dispersive X-ray micro-analyzer (EDAX)(Cam-Scan MV 2300). Prior to the SEM studies, the samples were coated with a thin gold layer. Free cells in solution were counted by direct counting using a Thoma chamber of 0.1 mm depth and 0.0025 mm² area with an optical microscope ($\times 1500$, model: Zeiss-

Axioskop 40). All analytical measurements were carried out in triplicate for each sample to ensure the reliability of the process.

2.4. Apparatus

The leaching experiments were performed in a double-wall, three-chamber, three-electrode, two-liter glass electrobioreactor with four baffles, thermostated at the desired temperatures of 35 °C or 50 °C (Fig. 1). A reticulated titanium–platinum working electrode (15 cm \times 9 cm \times 0.1 cm, 4 pixels per inch) was immersed into the cathodic compartment. A platinum foil as a counter electrode was put into the anodic compartment filled with 9 K medium (initial pH of 1.8). Cathode chamber was separated from anode by a fritted glass. The reference electrode was Ag/AgCl connected to the electrolyte in the main chamber through a capillary, which ended close to the working electrode. The potential of the working electrode was controlled with respect to the reference electrode using a Solartron SI 1287 potentiostat. Air was supplied at a rate of 1.3 L min^{−1} through a ring sparger under a pitched-blade impeller.

2.4. Experimental procedure

This study consisted of the four types of experiments namely, chemical leaching (CL), electrochemical leaching (ECL), bioleaching (BL) and electrochemical bioleaching (EBL). Chemical leaching tests were carried out as observing runs at 35 °C and 50 °C and a pH of about 1.8. The electrochemical leaching experiments were performed under controlled potential and otherwise the same conditions as chemical leaching. To eliminate the bacterial activities during chemical and electrochemical runs, a desired volume of a thymol-metanol solution were used (0.2% v/v). Bacterial leaching runs were carried out at 35 °C using mesophilic and at 50 °C using moderately thermophilic bacteria. Electrochemical bioleaching experiments were performed at the desired potential between 400 and 450 mV and otherwise under the same conditions as the related bacterial leaching tests. Initially, the cultures of an initial population of about 2×10^8 cells/ml were adapted by the copper concentrate up to a solid content of 10% (w/v). At the start of each experiment, the reactor was inoculated with 250 ml mixed culture of mesophilic or moderately thermophilic bacteria from the previous experiment (9 K medium). The indicators to change a medium with higher solid content were the solution ORP (to about 550 for moderate thermophiles and 650 for mesophiles), and microscopically counted cells (growing bacteria up the stationary phase). The main experiments were carried out with an initial pulp density of 10%. Based on the results of the primary tests and in order to allow optimum adaptation of microorganisms in the new medium, the bioleaching and electrobioleaching experiments were started with an agitation rate of about 300 rpm. To avoid particle sedimentation and achieve a

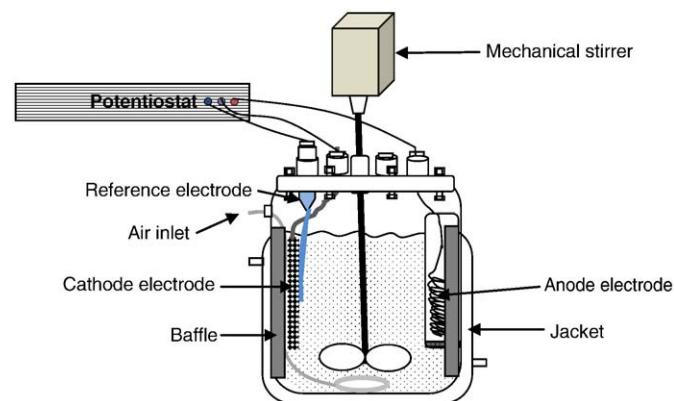


Fig. 1. Schematic illustration of thermostated electrobioreactor.

Table 1
Mineralogical composition of the sample.

Mineral	Chalcopryrite	Covellite	Chalcocite	Pyrite	Metallic (total)	Non metallic (total)	Oxides (total)
(wt. %)	44.02	6.78	5.84	23.99	81.60	13.61	4.79

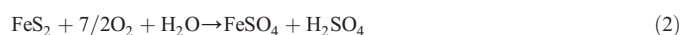
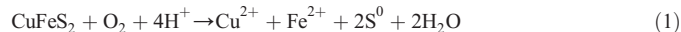
homogenous pulp, the agitation rate was increased to about 450 rpm after 4 days. Periodically, 15 ml pulp samples were withdrawn from the reactor and centrifuged for 5 min at 2500 rpm (model:SIGMA 3–16) to remove the solids. The solid recovered after centrifugation was returned to the reactor. The volume of the evaporated liquid was daily replaced by adding acidified distilled water.

3. Results and discussion

It is generally believed that even in high acidic solutions, the passivity of chalcopyrite surface by an iron-bearing precipitate is responsible for slow and incomplete extraction of copper. In order to improve the dissolution rate of chalcopyrite, the formation of the so called passive layer must be prevented. One of the most discussed solution for this problem, is the possible control of pulp oxidation reduction potential (ORP) during the bioleaching process. To evaluate the influence of the electrochemical reactions on copper recovery during chemical and bacterial leaching, the results reported in this work focus on the comparison between processes in which the ORP was controlled and the classic bioleaching experiments.

3.1. Variation of ORP

The solution ORP during (bio)-leaching of chalcopyrite concentrate depends on the ferric to ferrous ion ratio ($\text{Fe}^{3+}/\text{Fe}^{2+}$) as described by the Nernst equation (Rossi, 1990). The ferrous ions formed from chemical leaching of chalcopyrite (Eq. (1)) and pyrite (Eq. (2)) or electroreduction of ferric ions (in electrochemical bioleaching) (Eq. (3)), decrease the ORP while microbial oxidation (Eq. (4)) or chemical oxidation by air injected to the reactor (Eq. (4)) increase the ORP by the regeneration of ferric ions.



In Fig. 2, the selected results of ORP variation as a function of leaching time are presented. The experiments were performed at a pulp density of 10%. These tests included chemical leaching at 50 °C, bioleaching with mesophilic bacteria at 35 °C and bioleaching with moderately thermophilic bacteria at 50 °C. The results show that after

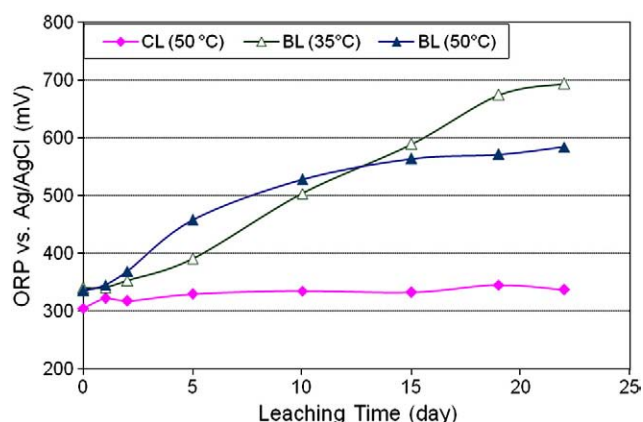
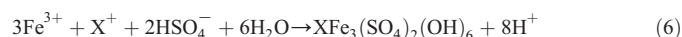
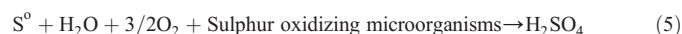


Fig. 2. ORP variation as a function of leaching time for different experimental: chemical leaching (CL), and bacterial leaching (BL).

an adaptation period during the lag phase, the ORP values increase from about 340 to about 690 mV (after 22 days), and from 330 to about 590 mV (after 22 days) for mesophilic and moderately thermophilic cultures, respectively. Lower ORP values in the moderately thermophilic culture were probably due to oxygen dissolution limitations at 50 °C compared to that at 35 °C. However, ORP values in both sterile runs (chemical leaching) remained constant around 310–350 mV. It was also observed that pH values of solution generally decrease with increasing ORP. The reduction of pH could inhibit the formation of jarosite that can act as a passive layer. There are three main reasons for the strong decrease of the pH. These include the bacterial conversion of sulfur and sulfide species to sulfate as stated by Eq. (5), the dissolution of pyrite (Eq. (2)) and the precipitation of jarosite according to Eq. (6) (Gupta and Mukherjee, 1990).



Where $\text{X} = \text{K}^+, \text{Na}^+, \text{NH}_4^+$ or H_3O^+

During electrochemical leaching and electrochemical bioleaching runs, the ORP in the cathodic compartment of the electro-bioreactor was controlled at the desired levels, while the pH gradually increased, whereas at the anodic compartment, the ORP gradually increased and the pH decreased. On the other hand, a higher ability of mesophilic bacteria to oxidize Fe (II) could lead to more current flow through the electrolyte that decreased the ORP and regulated it at the desired value.

3.2. Copper and iron leaching

Results of copper and iron dissolution as a function of leaching time for different process under otherwise similar conditions ($T = 35^\circ\text{C}$, initial pH = 1.8 and a pulp density of 10%) are presented in Figs. 3 and 4. According to the results, the chemical leaching (CL) of the sample leads to about 9% copper recovery after 4 days which increases to a maximum of around 14% after 22 days. The dissolution rate of copper after about 1 day decreases with increasing leaching time. In average, about 6% more copper can be leached under the same conditions, when the process is performed under a controlled ORP during electrochemical leaching (ECL). In this case, the maximum copper recovery should be around 20% after 22 days. In the presence of mesophilic microorganisms and under uncontrolled potential (Bioleaching tests (BL), the copper dissolution during the lag phase of about four days is slightly more than that obtained from chemical

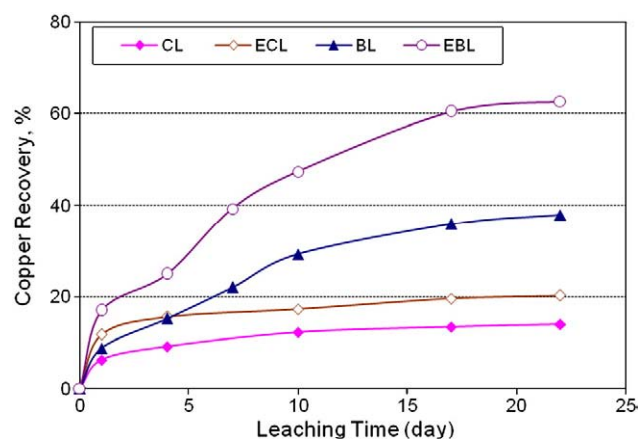


Fig. 3. Copper recovery as a function of leaching time at 35 °C for different experimental conditions: chemical leaching (CL), electrochemical leaching (ECL), and bacterial leaching (BL), electrochemical bioleaching (EBL).

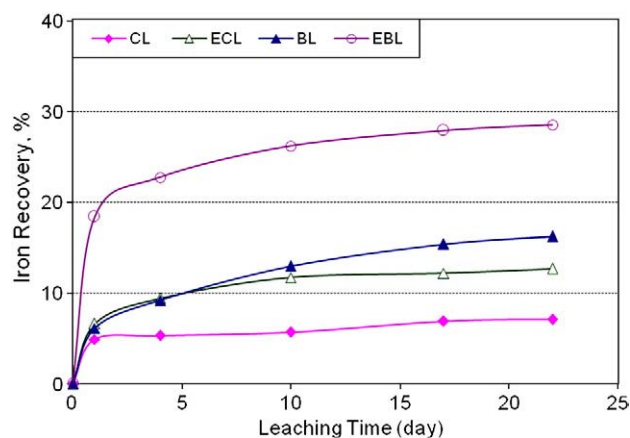


Fig. 4. Total iron recovery as a function of leaching time at 35 °C for different experimental conditions: chemical leaching (CL), electrochemical leaching (ECL), and bacterial leaching (BL), electrochemical bioleaching (EBL).

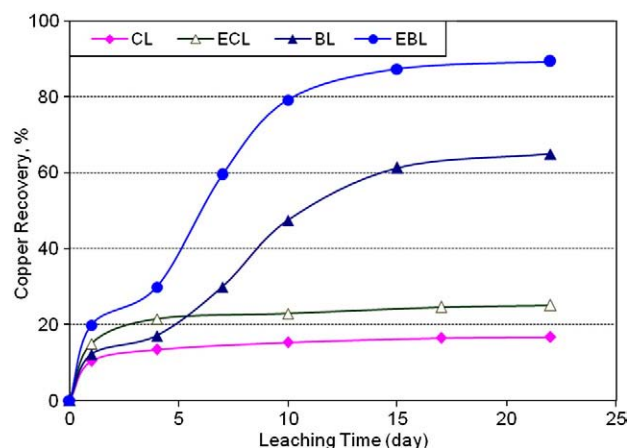


Fig. 5. Copper recovery as a function of leaching time at 50 °C for different experimental conditions: chemical leaching (CL), electrochemical leaching (ECL), and bacterial leaching (BL), electrochemical bioleaching (EBL).

leaching. The main reason for this higher copper extraction in this period is the presence of copper and iron in the solution inoculated to the slurry. The dissolution rates significantly increase after adaptation period of microorganisms. After about 10 days, the cumulative copper recovery by bioleaching is higher than that by electrochemical leaching. Under this condition, about 38% of total copper can be leached after about 20 days. The copper and iron dissolution rates (Figs. 3 and 4) show typical parabolic behavior generally associated to the progressive passivation of sulfide ore surface. On the other hand, iron dissolves relatively much slower than copper under the same conditions, which leads to copper/iron ratio of about 2 in the solutions. That could mean a fraction of iron remains as jarosite on the surfaces of chalcopyrite which was confirmed by SEM/EDAX analyses (Fig. 7B). The limited formation of jarosite during electrochemical bioleaching process (Fig. 7D) is believed to be the main reason for increasing copper and iron dissolution. Compared to the bioleaching process, about 25% more copper and more than 12% iron could be dissolved during electrochemical bioleaching experiments (Figs. 3 and 4). However, the final copper recovery of about 62% is not high enough to justify the commercial application of the electrochemical bioleaching with mesophilic microorganisms. Therefore, in the second part of this study, the same experiments were performed using moderately thermophilic bacteria at 50 °C. Results of copper and iron dissolution as a function of leaching time for different process conditions are presented in Figs. 5 and 6. Compared to the chemical and electrochemical leaching experiments at 35 °C (Figs. 3 and 4), the maximum iron recoveries at 50 °C are 8.2% (CL), and 19.3% (ECL) which is about 1.5% higher in average. This should be related to the influence of higher temperature. However, in the presence of moderately thermophilic bacteria, the total dissolution of chalcopyrite is drastically increased with respects to the experiments conducted at 35 °C in the presence of mixed mesophilic cultures. From the results presented in Figs. 5 and 6, it can be seen that after a lag phase of about four days the copper and iron dissolution rates increases up to an operation time of about 15 days. At this time, the cumulative copper and iron recoveries are about 85% and 45%. These are about 20% higher than that resulted from same experiments with mesophilic microorganisms at 35 °C. At longer operation times, the copper and iron dissolution rates show typical parabolic behavior. The copper recovery can be slightly increased to around 90% after 20 days. The same observation can be done for iron. In this case, iron dissolution rate is relatively high, which leads to a final solution with a copper/iron molar ratio of less than two. That means the formation of passive layer on the surface of chalcopyrite is obviously limited during the electrochemical bioleaching when the process is carried out at controlled potentials between 400 and 450 mV. Under conventional

bioleaching conditions (pulp density 10% w/v), maximum copper recovery is around 37% or 65% after 22 days in the presence of mesophilic or moderately thermophilic cultures, respectively.

The results in Figs. 5 and 6 also indicate that in the case of pure chemical leaching (inhibition of bacterial activity by thymol), the copper dissolution from chalcopyrite concentrate did not exceed 17% even at 50 °C. It can be postulated that during chemical leaching and electrochemical leaching the dissolved copper is mainly originated from secondary sulfide minerals such as covellite and chalcocite. It is believed that the high lattice energy of chalcopyrite and its low solubility in such solutions are responsible for the low copper dissolution. Comparison of ORP variation (Fig. 2) with related copper recoveries (Figs. 3 and 5) indicates a relationship between ORP and metal dissolution, which confirms the results of other investigations in which is reported that the dissolution rate of chalcopyrite and also the formation of a passive layer on the surface of chalcopyrite are strongly dependant on the ORP of solution (Hiroyoshi et al., 2008; Pinches et al., 2001; Third et al., 2002; Cordoba et al., 2008). Lower copper recovery in the presence of mesophilic culture compared to moderately thermophilic culture is attributed to its higher ORP values (680 compared to 560 mV) and lower temperature.

Results of this study show that in all experiments the extraction of iron is significantly lower than that of copper. The reasons for the low iron dissolution in the electrochemical bioleaching and bioleaching processes may be different. In the electrochemical bioleaching process at low solution potentials, the low leachability of pyrite (Eq. (2)) as a

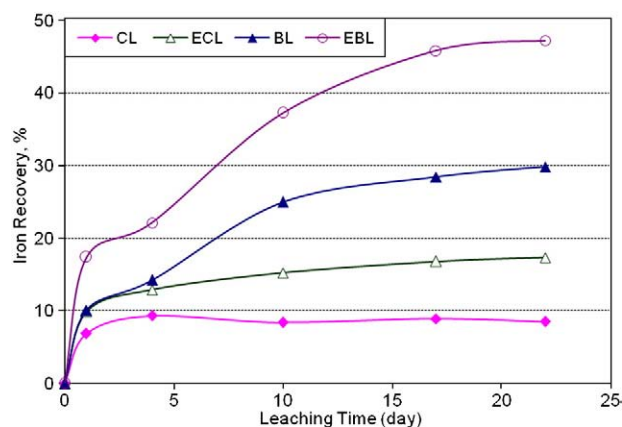


Fig. 6. Total iron recovery as a function of leaching time at 50 °C for different experimental conditions: chemical leaching (CL), electrochemical leaching (ECL), bacterial leaching (BL), and electrochemical bioleaching (EBL).

major iron containing phase may be the main reason, while in the bioleaching experiment, the precipitation of a part of dissolved iron as jarosite at high ORP (high Fe (III) concentrations) should be responsible for low iron concentration in the leach solutions.

In the electrochemical bioleaching mode, current passes across the cathode and anode and several electrochemical reactions can occur. At the cathode compartment, the main opposing reactions that influence the solution ORP are reactions (1)–(4). These include the release of Fe (II) ions to the solution as a result of chalcopyrite and pyrite leaching (Eqs. (1) and (2)), the bacterial oxidation of Fe (II) by iron oxidizing bacteria in the presence of oxygen as an electron acceptor and the chemical oxidation of Fe (II) by oxygen of the air injected into the pulp (Eq. (4)), and the electrochemical reduction of Fe (III) (Eq. (3)). Other cations such as Cu^{2+} and H^+ present in the solution are more electropositive than Fe (III), therefore they don't get discharged at applied potentials above 200 mV (vs. Ag/AgCl) investigated in this study. However, if the cell operates at currents above the limiting levels of the desired reactions or in the case of slow migration and diffusion of Fe (III) ions to the cathode electrode, a significant portion of the applied current may be consumed by undesirable reactions. In practice, transport limitations of Fe (III) to the electrode surface are observed at low stirring rates and at solutions with low Fe (III) concentration.

A gradual increase of pH occurs in the catholyte especially in the presence of mesophilic bacteria. The pH increase may be caused by the reduction of protons as a consequence of high current passing across the electrolyte, low solubility of pyrite as an acid producer (Eq. (2)) at low ORPs, and lower hydrolysis of Fe (III) (Eq. (6)). In the anodic compartment, water decomposes on the platinum anode and generates oxygen and protons according to the following equation:

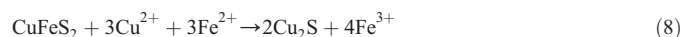


The water decomposition leads to the formation of a highly corrosive medium due to a very low pH value and a very high solution potential (~1200 mV), so the anode should be one of the noblest materials such as pure platinum. Carbon anode was not stable in this very corrosive medium. A gradual corrosion of carbon was observed during our tests. In addition to the decomposition of water, hydroxyl ions are also oxidized at the anode, but their concentration in the acidic solution is too low as this reaction accounts for very little anodic currents. Moreover, since the electrode potentials required for the oxidation of sulfate anions are much greater than that for the decomposition of water (Gupta and Mukherjee, 1990), these reactions does not take place at all.

It should be explained that the electrochemical transformations in electrobioleaching have two distinct influences on biological and chemical subsystems which lead to increasing copper dissolution. In the biological subsystem, as counted by microscopic observations, the concentration of mesophilic cells increased from about 3×10^6 to 5×10^8 cell/ml and that of moderately thermophilic cultures from about 2×10^6 to 4×10^8 cell/ml after 5 days. This number is about fourfold higher than those for the conventional bioleaching mode under similar conditions. Obviously the increased reduction of Fe(III) to Fe(II) during electrochemical bioleaching process leads to higher Fe (II) concentration in the solution which can act as a nutrient for iron oxidizing bacteria and therefore positively affects on their growth and activity. This observation is in agreement with results reported by Natarajan (1992) and Nakasono et al. (1997). Kelly and Jones (1978) reported that the increasing of Fe(II) concentration up to 0.1 M enhances the oxygen uptake rate by bacteria. Low bacteria/solid ratio has been reported as one of the important parameters that reduces the bioleaching efficiency at higher pulp densities (Bailey and Hansford, 1999).

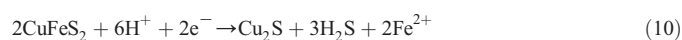
In the chemical subsystem as proposed by Hiroyoshi et al. (1997, 2000, 2001), chalcopyrite can be dissolved at a high rate in low ORP

values. It is believed that chalcopyrite dissolves in two steps according to the Eqs. (8) and (9). The ORP has to be low enough for chalcocite formation and high enough for the subsequent chalcocite oxidation (~400–450 mV).



In the presence of microorganisms, elemental sulfur is oxidized to sulfate (Eq. (5)) and Fe(II) is oxidized to Fe(III) (Eq. (4)) by sulfur- and iron-oxidizing bacteria, respectively. At steady state in electrobioleaching, the rate of Fe(II) oxidation reactions in the working compartment are in equilibrium with the rate of Fe(III) reduction reactions, so the solution ORP and the concentration ratio of Fe(III) to Fe(II) remain constant during the process.

In the case of electrobioleaching, there is a periodic electrical contact between semiconducting metallic sulfide minerals such as chalcopyrite and the working electrode which leads to higher charging of these particles. Biegler and Horn (1985) showed that chalcopyrite can be electrochemically reduced to an iron-free copper sulphide product whose composition can be in the range of $\text{Cu}_{1.8}\text{S}$ to Cu_2S (Eq. (10)). At current densities below 10 mA/cm² chalcocite can be formed; however, at higher current densities the solid product contained elemental copper.



H_2S produced in the above equation could be oxidized in the presence of Fe (III) (Eq. (11)) or precipitated as covellite in the presence of Cu^{2+} (Eq. (12)).



Furthermore, it is generally believed that high Fe(III) concentration in solutions originated from conventional bioleaching of sulfide minerals are responsible for the formation of iron-hydroxyl precipitates as a barrier for mineral dissolution. From the results of this study, it can be concluded that the controlled potential in electrochemical bioleaching process of chalcopyrite concentrate in the presence of moderate thermophiles, significantly reduces the formation of iron oxy-hydroxide on the surface of chalcopyrite by increased reduction of Fe(III) to Fe(II). As a result of this process, electrochemical dissolution of chalcopyrite and copper recovery can be increased. This conclusion is confirmed by SEM/EDAX analysis of the leaching residues. In order to investigate the effect of bacterial activities on the surface behavior of chalcopyrite concentrate, the morphologies of the conventional and electrochemical bioleaching residues were examined using SEM photographs, in addition to their elemental compositions with EDAX microanalyses (Fig. 7). These micrographs show that obviously the surface of solid residues after the conventional bioleaching and electrochemical bioleaching processes differ from that of original sample (Fig. 7A). It can be seen that the surface of solid residues after bacterial leaching at 35 °C and 50 °C (in its some areas) are covered with an amorphous iron oxy-hydroxide layer (Fig. 7B and C). The decrease in the reactivity of the concentrate was presumably due to the formation of this layer. However, under electrochemical bioleaching conditions (ORP around 425 mV), the dissolution of copper is more efficient especially in the presence of moderately thermophilic bacteria. These results support the conclusion that in presence of moderately thermophiles under controlled potential, the formation of jarosite on the surface of chalcopyrite, which can act as a diffusion barrier and prevent chalcopyrite dissolution, is significantly reduced.

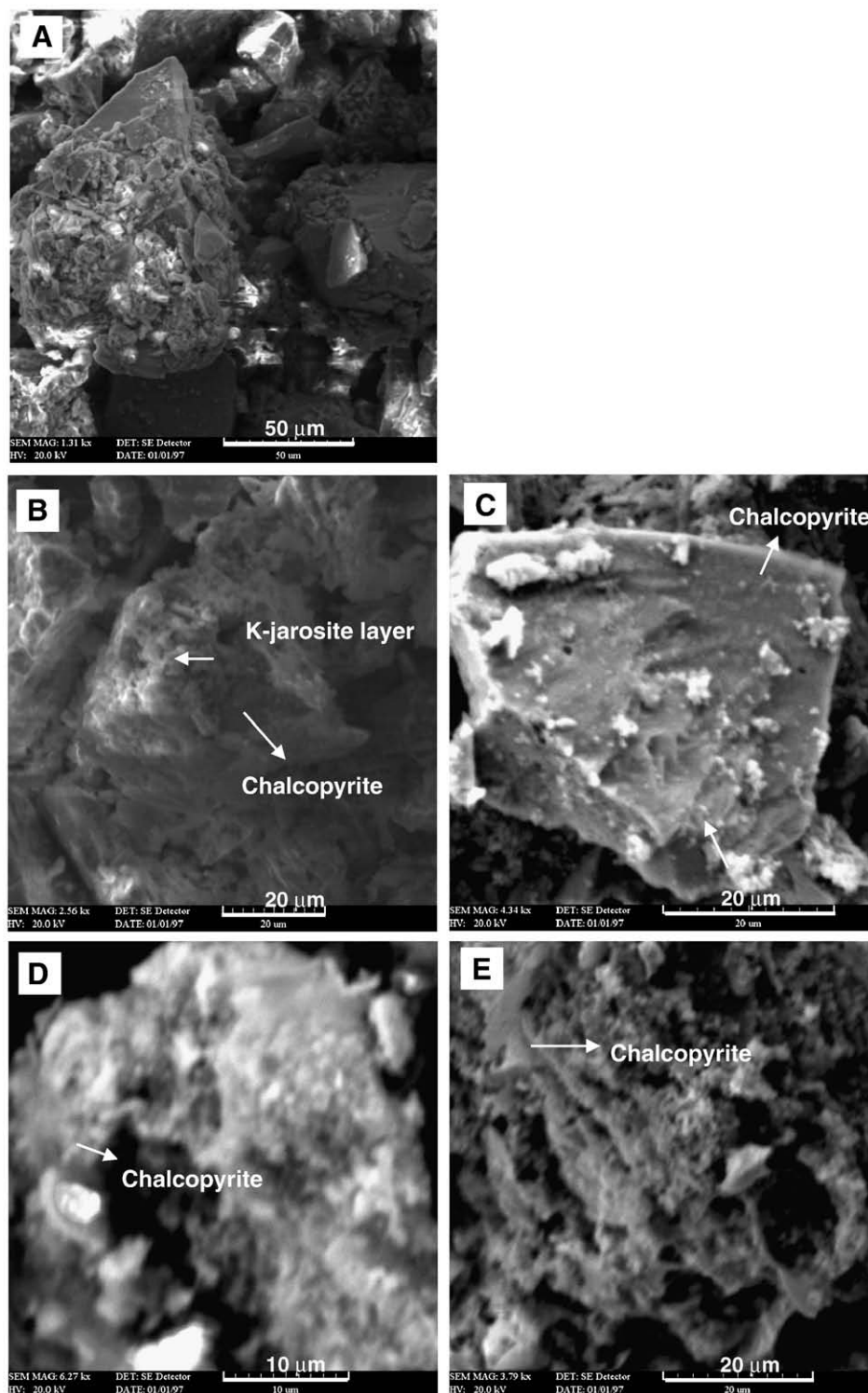


Fig. 7. SEM microphotographs of feed (A); solid residues of (B) bioleaching with mesophilic bacteria, (C) bioleaching with moderately thermophilic bacteria, (D) electrobioleaching with mesophilic bacteria and (E) electrobioleaching with moderately thermophilic bacteria.

4. Concluding remarks

- 1) Compared to the chemical leaching and bioleaching, the copper recovery by electrochemical bioleaching could be increased up to 35%. At optimum condition around 90% of copper could be leached from the chalcopyrite concentrate.
- 2) The cell concentrations in the electrochemical bioleaching increase drastically up to an excellent level near to 10^9 cells/ml, which is about fourfold higher than those levels in conventional bioleaching.

- 3) SEM-EDAX analysis of the solid residues shows clear differences in the composition of reaction products during bioleaching and electrochemical bioleaching. Applying potential to the slurry significantly reduced the formation of jarosite that is known as a barrier for chalcopyrite dissolution.
- 4) From the results of this study, it can be concluded that an electrochemical bioleaching process has an excellent potential to be used for copper recovery from chalcopyrite concentrate in industrial scales. However, even when copper recovery is high

enough to justify the process economically, the objective of the second phase of this program is to evaluate the optimum process conditions for solid densities up to 20%. This should increase the industrial application potential of this process.

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