

Accepted Manuscript

Synergistic bioleaching of chalcopyrite and bornite in the presence of *Acidithiobacillus ferrooxidans*

Hongbo Zhao, Jun Wang, Minghao Hu, Wenqing Qin, Yansheng Zhang,
Guanzhou Qiu

PII: S0960-8524(13)01459-4

DOI: <http://dx.doi.org/10.1016/j.biortech.2013.09.035>

Reference: BITE 12400

To appear in: *Bioresource Technology*

Received Date: 23 July 2013

Revised Date: 3 September 2013

Accepted Date: 6 September 2013

Please cite this article as: Zhao, H., Wang, J., Hu, M., Qin, W., Zhang, Y., Qiu, G., Synergistic bioleaching of chalcopyrite and bornite in the presence of *Acidithiobacillus ferrooxidans*, *Bioresource Technology* (2013), doi: <http://dx.doi.org/10.1016/j.biortech.2013.09.035>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.



Synergistic bioleaching of chalcopyrite and bornite in the presence of *Acidithiobacillus ferrooxidans*

Hongbo Zhao^{a,b*}, Jun Wang^{a,b*}, Minghao Hu, Wenqing Qin^{a,b}, Yansheng Zhang^{a,b}, Guanzhou Qiu^{a,b}

^a Key Lab of Biohydrometallurgy of Ministry of Education, Changsha 410083, Hunan, PR China

^b School of Minerals Processing & Bioengineering, Central South University, Changsha 410083, Hunan, PR China

Abstract: Bioleaching of chalcopyrite and bornite in the presence of *Acidithiobacillus ferrooxidans* was carried out to investigate the influences between each other during bioleaching. Bioleaching results indicated that bornite accelerated the dissolution of chalcopyrite, and chalcopyrite also accelerated the dissolution of bornite, it could be described as a synergistic effect during bioleaching, this synergistic effect might be attributed to the galvanic effect between chalcopyrite and bornite, and to the relatively low solution potential as the addition of bornite. Significantly amount of elemental sulfur and jarosite formed on the minerals surface might be the main passivation film inhibiting the further dissolution, and the amount of elemental sulfur significantly increased with the addition of bornite. Results of electrochemical measurements indicated that the oxidation and reduction mechanisms of chalcopyrite and bornite were similar, the addition of bornite or chalcopyrite did not change the oxidative and reductive mechanisms, but increased the oxidation rate.

Key words: Synergistic bioleaching; Chalcopyrite; Bornite; *Acidithiobacillus ferrooxidans*

1. Introduction

Bioleaching has been successfully applied in the processing of secondary copper sulfide minerals, it is still not efficient and economic to process primary copper sulphide minerals like chalcopyrite (CuFeS_2) and bornite (Cu_5FeS_4) (Bosecker, 1997; Watling, 2006). However, chalcopyrite and bornite are the most abundant copper

*Corresponding author. Address: Key Lab of Biohydrometallurgy of Ministry of Education, Changsha 410083, China.

Tel: +86-15116335985; E-mail: alexandercsu@126.com (Hongbo Zhao)

Tel: +86-731-88876557; E-mail: wjq2000@126.com (Jun Wang).

minerals(Kesler & Wilkinson, 2008; Rohwerder et al., 2003). Therefore, the industrial application of bioleaching of chalcopyrite and bornite has a broad prospect.

Many authors have concluded that the low extraction rate and dissolution kinetics of chalcopyrite in bioleaching are caused by passivation film, which was considered to be jarosite, elemental copper and metal-deficient sulfides (Córdoba et al., 2008; Hackl et al., 1995; Tshilombo, 2006). Bornite, as its relatively lower lattice energy, could be better dissolved in bioleaching mediums, while its extraction rate and dissolution kinetics are still not high enough (Bevilaqua et al., 2010; Rohwerder et al., 2003; WANG et al., 2008).

Some authors pointed out that higher extraction rate could be obtained by controlling the solution potential at a relatively low value, even though the specific mechanisms are still not explicit(Ahmadi et al., 2010; Natarajan, 1992; Qin et al., 2012). And many researches revealed that the addition of minerals with higher electrostatic potential could accelerate the dissolution of minerals with lower electrostatic potential mainly caused by galvanic effect (Attia & El-Zeky, 1990; Li et al., 2003; Nakazawa et al., 1998).

Acidithiobacillus ferrooxidans was the first strain applied in the bioleaching of copper sulphide minerals, and also was considered as the dominate population in most acid mine drainage (AMD) of sulfide minerals mines as its strong abilities to oxidize ferrous ions and sulfur (Ramírez et al., 2004; Thurston et al., 2010).

Therefore, bioleaching of chalcopyrite and bornite in the presence of *Acidithiobacillus ferrooxidans* were carried out to investigate the influences between each other, and to increase the leaching kinetics and copper extraction rate in bioleaching the first time.

2. Materials and methods

2.1 Minerals and reagents

The X-ray diffraction analysis and chemical elements analysis of ore samples showed that both chalcopyrite and bornite were of high purity. Chalcopyrite contains 37.94% of copper, 26.1% of iron, and 31.96% of sulfur. Bornite contains 61.59% of copper, 9.92% of iron, and 22.52% of sulfur. Ore samples were ground and screened

to -0.074 mm before used for bioleaching experiment. All chemicals used for electrochemical measurement were of analytical grade.

2.2 Microorganism and growth conditions

Acidithiobacillus ferrooxidans used was obtained from the Key Lab of Biohydrometallurgy of Ministry of Education, Central South University, Changsha, China, bacteria was cultured in 250 mL shake flasks using an orbital incubator with a stirring speed of 200 r/min at 30°C. The 9K medium used for cell cultivation consisted of the following components: (NH₄)₂SO₄ (3.0 g/L), MgSO₄·7H₂O (0.5 g/L), K₂HPO₄ (0.5 g/L), KCl (0.1 g/L), Ca(NO₃)₂ (0.01 g/L). All the bacterial cultures were sub-cultured into basal salts medium supplemented with ferrous sulphate (FeSO₄) as the energy source. The resulting culture was used as inoculums for the bioleaching experiments.

2.3 Bioleaching experiment

10 mL cells were inoculated into a 250-mL shake flask containing 90 mL of sterilized 9 K medium and 5 g minerals, the minerals were composed of chalcopyrite and bornite with different ratios of 5:0 (1#), 4:1 (2#), 3:2 (3#), 2:3 (4#), 1:4 (5#) and 0:5 (6#). The shake flasks were placed into an orbital shaker at 200 r/min and 30°C, pH value was adjusted to 1.6 by sulfuric acid regularly, and water lost by evaporation was supplemented periodically by adding sterile 9K medium. During the bioleaching process, record the variation of pH values, bacterial concentration and redox potentials regularly, as well as the copper concentration.

2.3.2 Calculation of acid consumption

The consumption of acid was represented by the amount of H⁺ consumption for per gram of ore each day, it could be calculated by the equation as Eq.(1).

$$N = (10^{-a} - 10^{-b}) \times 1000V / M \quad (1)$$

Where N is the consumption of H⁺ for per gram of ore, with unit of mmol/g; a is the pH value measured on former day (measured after adding sulfuric acid), b is the pH value measured on the following day (measured before adding sulfuric acid); V is the total volum of leaching solution, with unit of L; and M is the weight of added

minerals, with unit of g.

2.4 Electrochemical measurement

2.4.1 Electrodes

The Carbon Paste Electroactive Electrodes (CPEE) were made by mixing 0.7 g minerals (-0.038 mm), 0.2 g graphite and 0.1 g solid paraffin. The mixture was heated and then transferred rapidly into a tablet model for tableting under the pressure of 500 kg/cm², and then took out for air drying, the electrodes were polished using 600-grit silicon carbide paper to obtain smooth surface before electrochemical measurements (Takeuchi et al., 2007; Wang et al., 1998).

2.4.2 Cyclic voltammogram and tafel test

For the cyclic voltammograms test and tafel test, a conventional three-electrode system consisted of working electrode, graphite rod as counter electrode and Ag/AgCl (3.0 M KCl) electrode as reference electrode. The electrolyte used was composed of the following compositions: 3.0 g/L (NH₄)₂SO₄, 0.1 g/L KCl, 0.5 g/L K₂HPO₄, 0.5 g/L MgSO₄/L and 0.01 g/L Ca (NO₃)₂, the pH value of solution was adjusted to 1.6 by sulfuric acid. The electrochemical measurement was conducted on a Princeton Model 283 potentiostat (EG&G of Princeton Applied Research) coupled to a personal computer, cyclic voltammogram tests were carried out at a sweep rate of 10 mV/s, and tafel tests were carried out at a sweep rate of 0.5 mV/s.

2.5 Analytical techniques

The mineralogical compositions of solid samples were examined by X-ray diffraction (XRD) (DX-2700). The bacterial concentration was measured by microscope (CX31). Copper concentration was determined by inductively coupled plasma-atomic emission spectrometer (ICP-AES) (America Baird Co. PS-6). The pH values were measured with a pH meter (PHSJ-4A) and the redox potentials of leaching solution were measured by a Pt electrode with reference to a Ag/AgCl electrode (3.0 M KCl) (BPP-922).

3. Results and discussion

3.1 Bioleaching of chalcopyrite and bornite

Fig.1 showed the results of bioleaching, including the variation of bacterial

concentration, copper extraction rate, redox potential, H⁺ consumption and supplement sulfuric acid. Fig.1 (a) showed that the copper extraction rate of both chalcopyrite and bornite under sterile conditions were very low, and the presence of *Acidithiobacillus ferrooxidans* significantly increased the copper extraction of both chalcopyrite and bornite. The variation of bacterial concentration was shown in Fig.1 (b), the bacterial concentration of chalcopyrite and bornite bioleaching reached at a platform in the later stage of bioleaching, while the bacterial concentration of mixed minerals bioleaching still kept increasing, indicating a stronger bacterial activity, which could be beneficial for the bioleaching process.

Fig.1 (c) showed that the copper extraction rate of single chalcopyrite was about 30% after bioleaching for 30 days, while total copper extraction rate of mixed minerals increased to about 64% when the ratio of chalcopyrite and bornite was 3:2, this result indicated that the copper extraction rate of chalcopyrite in the mixture could be about 40% even if bornite in the mixture was assumed to be leached totally, thus bornite accelerated the dissolution of chalcopyrite. Similarly, the copper extraction rate of single bornite was about 60%, but the total copper extraction rate of mixed minerals increased to about 73% when the ratio of chalcopyrite and bornite was 1:4, the copper extraction rate of bornite of about 66% could be obtained even if the chalcopyrite in the mixture was assumed to be totally leached, thus chalcopyrite also accelerated the dissolution of bornite. Therefore, there was a synergistic effect between chalcopyrite and bornite during bioleaching.

The variations of redox potential shown as Fig.1 (d) indicated that the addition of bornite was beneficial for controlling the solution potential at a relatively low level, which could be beneficial for the dissolution of chalcopyrite as reported by some researchers, they considered that the first step of reduction of chalcopyrite to bornite or talnakhite is the rate-limiting step during bioleaching (Ahmadi et al., 2010; Natarajan, 1992; Qin et al., 2012). And the redox potential reached at a relatively stable value in the later stage of bioleaching, mainly because of the balance between consumption and producing of ferric ions as the formation of jarosite.



Where M is a monovalent cation, such as H_3O^+ , Na^+ , K^+ and NH_4^+ , etc.

Fig.1 (e) showed the variation of acid consumption for per gram of ores regularly, it indicated that the variations of acid consumption of ores containing bornite were similar in the first 5 days, and then differences emerged. The results revealed that bornite might be the main mineral dissolved in the initial stage of bioleaching as its lower electrostatic potential and lower lattice energy. The copper extraction rate of minerals containing bornite significantly increased with the increase of amount of adding chalcopyrite in the first 3 days, this might be attributed to the galvanic effect between chalcopyrite and bornite. Therefore, bornite was considered as the main mineral dissolved in the initial stage of mixed minerals bioleaching.

The initial stage of chalcopyrite bioleaching was a period of acid consumption, which could be mainly described as Eq.(3) and Eq.(4), while the amount of acid consumption decreased along with the bioleaching process, this might be mainly attributed to the chemical reactions producing sulfuric acid shown as Eq.(5)(Leahy & Schwarz, 2009; Zhou et al., 2009).

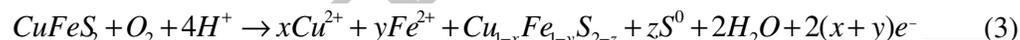
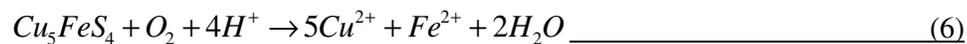


Fig.1 (f) indicated that total amount of supplement sulfuric acid during the whole bioleaching process increased along with the addition of bornite mainly as the dissolution of bornite was a process of acid consumption(Bevilaqua et al., 2010; Pestic & Olson, 1984).



X-ray diffraction (XRD) analysis indicated that a significant amount of jarosite and elemental sulfur was formed on the mineral surface after bioleaching. It could be observed that the amount of elemental sulfur increased with the addition of bornite, and jarosite kept at a significant amount with respect to any ratio of chalcopyrite and

bornite.

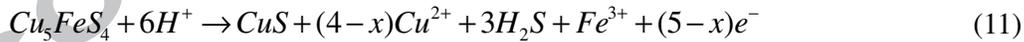
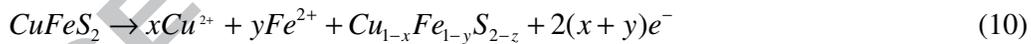
3.2 Electrochemical measurement

3.2.1 Cyclic voltammograms studies

Fig.2 showed the results of cyclic voltammograms test with sweep rate of 10 mV/s. During the anodic scan from -800 mV, three significant peaks of peak a, peak b, and peak c were detected for all the three electrodes, many researchers attributed them to the formation and further oxidation of chalcocite as shown in Eq.(7)-Eq.(9)(Arce & González, 2002; Lu et al., 2000; Qin et al., 2012). However, some others preferred peak c as the oxidation of hydrogen sulfide to elemental sulfur (Eghbalnia & Dixon, 2011; Elsherief, 2002; Liang et al., 2011).

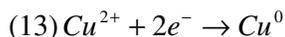
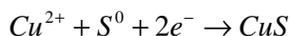


For the pre-wave of peak d at about 300-700 mV, it represented the decomposition of chalcopyrite and bornite to intermediate species as shown in Eq.(10)-Eq.(11)(Eghbalnia & Dixon, 2011; Zeng et al., 2013; Zeng et al., 2011). The current density of mixed minerals electrode was larger than that of the other two electrodes, indicating a higher oxidation rate, which was consistent with the bioleaching results.



In the reverse scan from 800 mV to -800 mV, two distinct peaks of peak e and peak f were observed for the three electrodes, peak e was reported as the reduction of ferric ions, copper ions and elemental sulfur (Eq.(12)-Eq.(14)), and peak f could be associated with reduction of covellite to chalcocite shown as Eq.(15), which was a reverse reaction of peak a(Cai et al., 2012; Ghahremaninezhad et al., 2010; Liu & Li, 2011).





(14)



Results of cyclic voltammograms tests indicated that the oxidation and reduction mechanisms of chalcopyrite and bornite were similar. The addition of bornite or chalcopyrite did not change the oxidative and reductive mechanisms, but increased the current density during oxidation process at 300-700 mV, that was in accordance with the bioleaching results.

3.2.1 Tafel studies

Fig.3 showed the tafel curves of the three electrodes, the sweep rate was 0.5 mV/s. The electrochemical parameters of corrosion potential (E_{corr}), corrosion current density (i_{corr}) and polarization resistance (R_p) were calculated. The corresponding corrosion potential of chalcopyrite, bornite and mixed mineral was 450 mV, 401.1 mV and 432.4 mV, the corresponding corrosion current density was 19.18 $\mu\text{A}/\text{cm}^2$, 6.114 $\mu\text{A}/\text{cm}^2$ and 29.41 $\mu\text{A}/\text{cm}^2$, the corresponding polarization resistance was 3.46 $\text{K}\Omega\cdot\text{cm}^2$, 6.97 $\text{K}\Omega\cdot\text{cm}^2$ and 2.25 $\text{K}\Omega\cdot\text{cm}^2$, respectively. It indicated that the mixed mineral has the largest corrosion current density and the lowest polarization resistance, resulting in a higher oxidation rate, which was consistent with the bioleaching results.

3.3 The model of interaction between chalcopyrite and bornite

A model of interaction between chalcopyrite and bornite during bioleaching was provided as shown in Fig.4. The surfaces of minerals were bacterial corrosion regions, where the complex interface reactions take place. It revealed that the galvanic effect accelerated the oxidative dissolution of bornite. And in the turn, the low solution potential mainly caused by the dissolution of bornite could be beneficial for the dissolution of chalcopyrite.

4. Conclusions

The synergistic effect between chalcopyrite and bornite existed during bioleaching in the presence of *Acidithiobacillus ferrooxidans*, it might mainly be

attributed to the galvanic effect between chalcopyrite and bornite, and to the relatively low solution potential as the addition of bornite.

Significant amount of elemental sulfur and jarosite could be the main passivation film inhibiting the further dissolution, and the amount of elemental sulfur significantly increased with the addition of bornite.

Electrochemical measurements revealed that the addition of bornite or chalcopyrite did not change the oxidative and reductive mechanisms, but increased the oxidation rate.

5. Prospects and future work

The relationship between chalcopyrite and bornite with different crystal structures during bioleaching in the presence of different strains of bacteria will be investigated, and the detailed transformation of surface phases will be studied in the future work.

Acknowledgments

This work was supported by Science Foundation of China (project No. 51374248), National High-tech Research and Development Program of China (project No. 2012AA061501), Research Fund for the Doctoral Program of Higher Education of China (project No. 20120162120010), and National Key Basic Research Program of China (project No. 2010CB630905) Natural.

References

- [1] Ahmadi, A., Schaffie, M., Manafi, Z., Ranjbar, M., 2010. Electrochemical bioleaching of high grade chalcopyrite flotation concentrates in a stirred bioreactor. *Hydrometallurgy*. 104, 99-105.
- [2] Arce, E.M., González, I., 2002. A comparative study of electrochemical behavior of chalcopyrite, chalcocite and bornite in sulfuric acid solution. *Int. J. Miner. Process.* 67, 17-28.
- [3] Attia, Y., El-Zeky, M., 1990. Effects of galvanic interactions of sulfides on extraction of precious metals from refractory complex sulfides by bioleaching. *Int. J. Miner. Process.* 30, 99-111.
- [4] Bevilaqua, D., Garcia Jr, O., Tuovinen, O., 2010. Oxidative dissolution of bornite by *Acidithiobacillus ferrooxidans*. *Process. Biochem.* 45, 101-106.

- [5] Bosecker, K., 1997. Bioleaching: metal solubilization by microorganisms. *Fems. Microbiol. Rev.* 20, 591-604.
- [6] Córdoba, E., Muñoz, J., Blázquez, M., González, F., Ballester, A., 2008. Leaching of chalcopyrite with ferric ion. Part I: General aspects. *Hydrometallurgy.* 93, 81-87.
- [7] Cai, Y., Chen, X., Ding, J., Zhou, D., 2012. Leaching mechanism for chalcopyrite in hydrochloric acid. *Hydrometallurgy.* 113, 109-118.
- [8] Eghbalnia, M., Dixon, D.G., 2011. Electrochemical study of leached chalcopyrite using solid paraffin-based carbon paste electrodes. *Hydrometallurgy.* 110, 1-12.
- [9] Elsherief, A., 2002. The influence of cathodic reduction, Fe²⁺ and Cu²⁺ ions on the electrochemical dissolution of chalcopyrite in acidic solution. *Miner. Eng.* 15, 215-223.
- [10] Ghahremaninezhad, A., Asselin, E., Dixon, D., 2010. Electrochemical evaluation of the surface of chalcopyrite during dissolution in sulfuric acid solution. *Electrochim. Acta.* 55, 5041-5056.
- [11] Hackl, R., Dreisinger, D., Peters, E., King, J., 1995. Passivation of chalcopyrite during oxidative leaching in sulfate media. *Hydrometallurgy.* 39, 25-48.
- [12] Kesler, S.E., Wilkinson, B.H., 2008. Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. *Geology.* 36, 255-258.
- [13] Leahy, M.J., Schwarz, M.P., 2009. Modelling jarosite precipitation in isothermal chalcopyrite bioleaching columns. *Hydrometallurgy.* 98, 181-191.
- [14] Li, H.X., Qiu, G.Z., Hu, Y.H., Wang, D.Z., 2003. Galvanic effect on mixed sulfide bioleaching. *Chinese Journal of Nonferrous Metals.* 13, 1287-1290.
- [15] Liang, C.L., Xia, J.L., Yang, Y., Nie, Z.Y., Zhao, X.J., Zheng, L., Ma, C.Y., Zhao, Y.D., 2011. Characterization of the thermo-reduction process of chalcopyrite at 65° C by cyclic voltammetry and XANES spectroscopy. *Hydrometallurgy.* 107, 13-21.
- [16] Liu, Q., Li, H., 2011. Electrochemical behaviour of chalcopyrite (CuFeS₂) in FeCl₃ solution at room temperature under differential stress. *Int. J. Miner. Process.* 98, 82-88.
- [17] Lu, Z., Jeffrey, M., Lawson, F., 2000. An electrochemical study of the effect of chloride ions on the dissolution of chalcopyrite in acidic solutions. *Hydrometallurgy.* 56, 145-155.
- [18] Nakazawa, H., Fujisawa, H., Sato, H., 1998. Effect of activated carbon on the bioleaching of chalcopyrite concentrate. *Int. J. Miner. Process.* 55, 87-94.
- [19] Natarajan, K., 1992. Bioleaching of sulphides under applied potentials. *Hydrometallurgy.* 29, 161-172.
- [20] Pesic, B., Olson, F., 1984. Dissolution of Bornite in sulfuric acid using oxygen as oxidant. *Hydrometallurgy.* 12, 195-215.
- [21] Qin, W., Yang, C., Lai, S., Wang, J., Liu, K., Zhang, B., 2012. Bioleaching of chalcopyrite by moderately thermophilic microorganisms. *Bioresource Technol.* 129, 200-208.
- [22] Ramírez, P., Guiliani, N., Valenzuela, L., Beard, S., Jerez, C.A., 2004. Differential protein expression during growth of *Acidithiobacillus ferrooxidans* on ferrous iron, sulfur compounds, or metal sulfides. *Appl. Environ. Microb.* 70, 4491-4498.
- [23] Rohwerder, T., Gehrke, T., Kinzler, K., Sand, W., 2003. Bioleaching review part A. *Appl. Microbiol. Biot.* 63, 239-248.
- [24] Takeuchi, R.M., Santos, A.L., Padilha, P.M., Stradiotto, N.R., 2007. Copper determination in ethanol fuel by differential pulse anodic stripping voltammetry at a solid paraffin-based carbon paste electrode modified with 2-aminothiazole organofunctionalized silica. *Talanta.*

71, 771-777.

- [25] Thurston, R.S., Mandernack, K.W., Shanks, W.C., 2010. Laboratory chalcopyrite oxidation by *Acidithiobacillus ferrooxidans*: Oxygen and sulfur isotope fractionation. *Chem. Geol.* 269, 252-261.
- [26] Tshilombo, A.F., 2006. Mechanism and kinetics of chalcopyrite passivation and depassivation during ferric and microbial leaching. PhD Thesis. University of British Columbia, Vancouver, BC, Canada.
- [27] Wang, H., Zhang, A., Cui, H., Liu, D., Liu, R., 1998. Adsorptive stripping voltammetric determination of phenol at an electrochemically pretreated carbon-paste electrode with solid paraffin as a binder. *Microchem. J.* 59, 448-456.
- [28] WANG, J., QIN, W.Q., ZHANG, Y.S., YANG, C.R., ZHANG, J.W., NAI, S.S., SHANG, H., QIU, G.Z., 2008. Bacterial leaching of chalcopyrite and bornite with native bioleaching microorganism. *T. Nonferr. Metal. Soc.* 18, 1468-1472.
- [29] Watling, H., 2006. The bioleaching of sulphide minerals with emphasis on copper sulphides—a review. *Hydrometallurgy.* 84, 81-108.
- [30] Zeng, W., Qiu, G., Chen, M., 2013. Investigation of Cu-S intermediate species during electrochemical dissolution and bioleaching of chalcopyrite concentrate. *Hydrometallurgy.* 134-135, 158-165.
- [31] Zeng, W., Qiu, G., Zhou, H., Chen, M., 2011. Electrochemical behaviour of massive chalcopyrite electrodes bioleached by moderately thermophilic microorganisms at 48° C. *Hydrometallurgy.* 105, 259-263.
- [32] Zhou, H.B., Zeng, W.M., Yang, Z.F., Xie, Y.J., Qiu, G.Z., 2009. Bioleaching of chalcopyrite concentrate by a moderately thermophilic culture in a stirred tank reactor. *Bioresource Technol.* 100, 515-520.

FIGURE CAPTIONS

Fig.1 The copper extraction rate of chalcopyrite and bornite by sterile leaching and bioleaching (a), the bacterial concentration (b), copper extraction rate (c), the redox potential (d), the H^+ consumption for per gram of ore (e) and the total supplement sulfuric acid (f) during bioleaching process (From 1#~6#, chalcopyrite : bornite=5:0, 4:1, 3:2, 2:3, 1:4, 0:5)

Fig.2 Cycle voltammograms of three electrodes

Fig.3 Polarization curves of three electrodes

Fig.4 The model of interaction between chalcopyrite and bornite in bioleaching

Figures

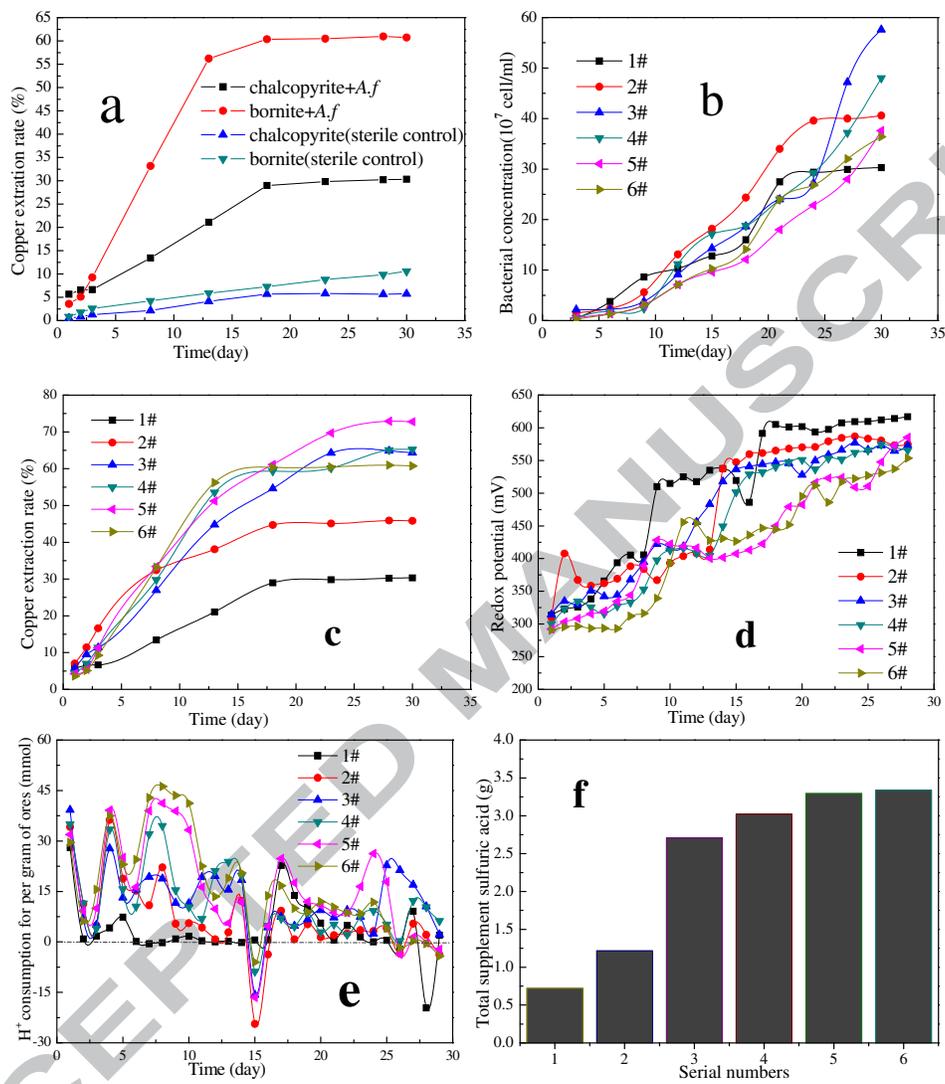


Fig.1

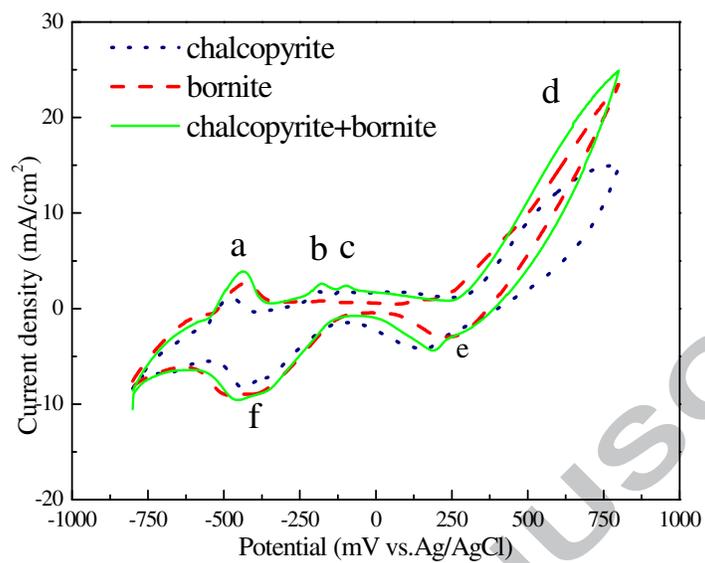


Fig.2

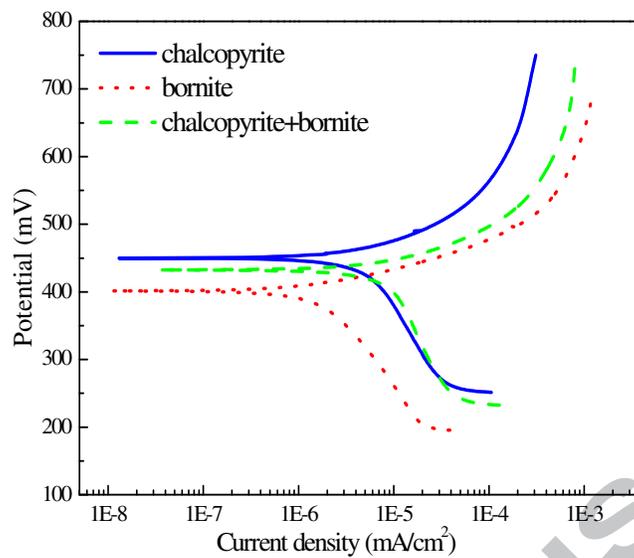


Fig.3

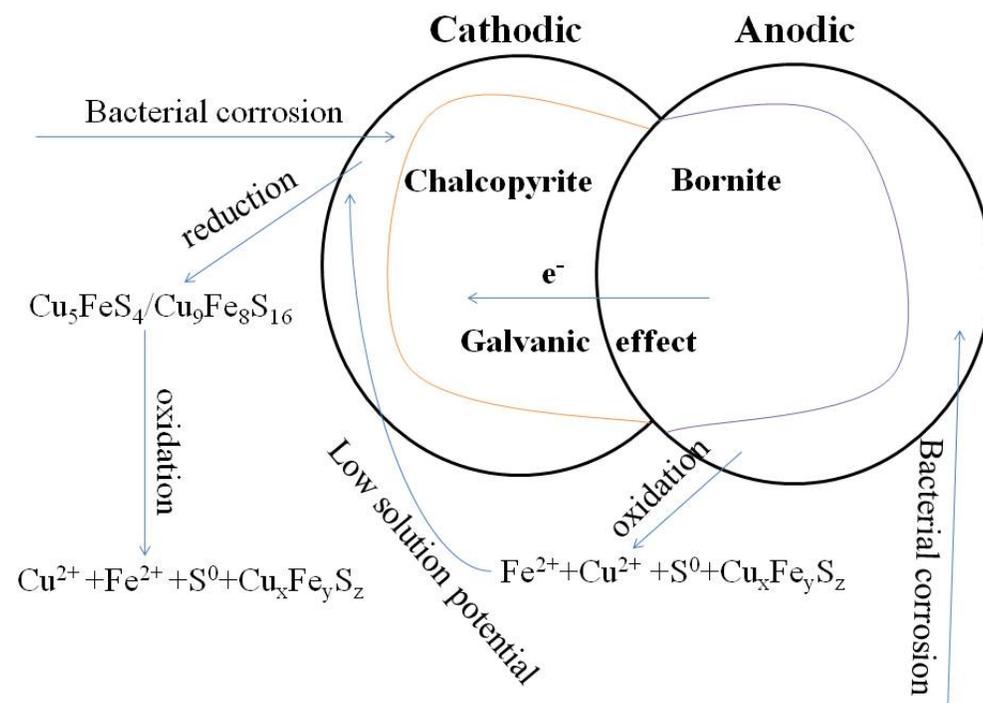


Fig.4

Highlights

- (1) A synergistic effect between chalcopyrite and bornite existed during bioleaching.
- (2) Galvanic effect and low solution potential caused the synergistic effect.
- (3) Addition of bornite or chalcopyrite did not change the dissolution mechanisms.
- (4) Oxidation rate increased as the addition of chalcopyrite or bornite.

ACCEPTED MANUSCRIPT