

Kinetics of copper dissolution from sulfidized chalcopyrite at high pressures in $\text{H}_2\text{SO}_4\text{--O}_2$

R. Padilla*, P. Pavez, M.C. Ruiz

Department of Metallurgical Engineering, University of Concepción, Edmundo Larenas 285, Concepción, Chile

Received 24 January 2007; received in revised form 10 October 2007; accepted 1 December 2007

Available online 8 December 2007

Abstract

The Sulfidation–Leaching process for the treatment of chalcopyrite concentrates is a non SO_2 polluting alternative for producing copper. This process consists of roasting chalcopyrite with sulfur at temperatures lower than 400 °C followed by leaching of the sulfidized material to dissolve the copper. The present work is concerned with the kinetic study of the pressure leaching of sulfidized chalcopyrite concentrate in $\text{H}_2\text{SO}_4\text{--O}_2$ solutions. The temperature range considered was 125–150 °C, and partial pressures of oxygen from 507 to 1216 kPa (5 to 12 atm). The results indicated that the copper dissolution rate increases with increasing temperature and partial pressure of oxygen. The leaching kinetics was analyzed by using a shrinking rim model given by: $1 - (1 - 0.45X)^{1/3} = kt$, which represented well the experimental data. The determined activation energy was 93.5 kJ/mol and the rate of copper dissolution was first order with respect to the partial pressure of oxygen.

© 2007 Elsevier B.V. All rights reserved.

Keywords: Pressure leaching; Chalcopyrite sulfidation; Autoclave; Covellite

1. Introduction

The conventional smelting/converting technology for copper making from chalcopyrite concentrates produces inevitably SO_2 , volatilized impurity compounds and substantial amounts of toxic dust. In spite of the significant advances in the capture of SO_2 and subsequent conversion of SO_2 to sulfuric acid to comply with the environmental regulations (Muñoz, 1996; Valenzuela et al., 2003), the copper production from chalcopyrite concentrates by smelting/converting route still presents serious environmental problems related to the gas emissions, especially in the converting step where complete SO_2 capture is difficult because of the intermittent production of SO_2 .

Alternatively, leaching of chalcopyrite concentrates has been considered for many years as a viable option to produce copper minimizing atmospheric pollution. However, direct leaching of chalcopyrite concentrates presents yet problems concerning the low dissolution kinetics of chalcopyrite (Dutrizac, 1982; Hackl et al., 1995) and problems concerning the precipitation and

disposal of the large amount of iron which dissolves along with the copper (Monhemius, 1996).

It has been known that the dissolution of the secondary copper sulfides such as covellite and chalcocite is much faster than the dissolution of chalcopyrite. For this reason, the leaching of secondary copper sulfide ores is a common industrial practice by using bacterial heap leaching with crushed ore (Jó et al., 1991; Gary et al., 1994) and recently pressure leaching of ground copper ore (Richmond, 2004).

On this matter, Padilla et al. (2003a,b,c) have developed a process that transforms the chemical composition of chalcopyrite into simple sulfides, which are more amenable to leaching. The process consists of chalcopyrite sulfidation with elemental sulfur at temperatures 350–400 °C. In this temperature range the transformation takes place with a fast rate and produces covellite (CuS) and pyrite (FeS_2) phases according to the following global reaction:



This sulfidation reaction is temperature limited. If the sulfidation of chalcopyrite is carried out at temperatures higher than 400 °C, the reaction products will be idaite (Cu_5FeS_6) and pyrite (Padilla et al., 2003a).

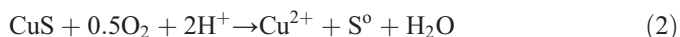
* Corresponding author.

E-mail address: rpadilla@udec.cl (R. Padilla).

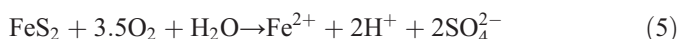
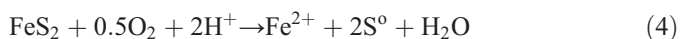
The product of sulfidation ($\text{CuS} + \text{FeS}_2$) is then leached for the extraction of copper in an appropriate leaching system. The leaching of the sulfidized material is faster than leaching a natural chalcopyrite and also it could be selective since copper and iron are present in separate phases.

Leaching of the sulfidation product in sulfuric acid–oxygen system is an attractive processing alternative since the resulting pregnant solution can be incorporated into the conventional leaching-purification-electrowining circuits. Therefore, the following is a brief discussion on the dissolution of covellite and pyrite in H_2SO_4 – O_2 media.

The covellite dissolution in this media has been shown to proceed according to the following reactions (Cheng and Lawson, 1991; Lotens and Wesker, 1987):



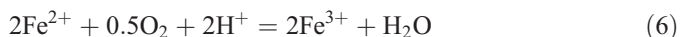
Similarly, the dissolution of pyrite can be represented by the following reactions (Bailey and Peters, 1976).



Reaction (2) is the most desirable in this system because the sulfur in the covellite reports to the solid residues as elemental sulfur. However, in practice, the proportion of sulfur and sulfate formed will depend on the leaching conditions. On the other hand, reactions (4) and (5) should be minimized for selective copper dissolution from materials that contain both copper and iron sulfides such as the sulfidized chalcopyrite.

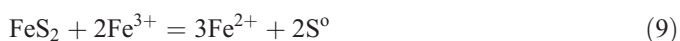
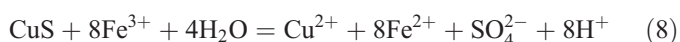
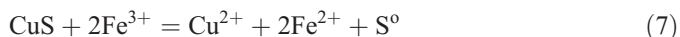
The leaching of CuS according to reaction (2) or (3) is very slow at atmospheric conditions; therefore, high temperatures and oxygen overpressures are required for the copper dissolution to occur at fast rates in sulfuric acid media (Cheng and Lawson, 1991).

It should be pointed out that under pressure leaching conditions the ferrous ions produced by the leaching of pyrite will eventually oxidize to ferric ions by oxygen according to:



Fe^{3+} is an effective oxidizing agent that can readily attack the metal sulfides; therefore, the indirect leaching mechanism involving oxidation of sulfides by Fe^{3+} coupled with re-oxidation of the Fe^{2+} by oxygen could play an important role in the pressure leaching of sulfidized chalcopyrite.

The reactions of covellite and pyrite with ferric ions to produce elemental sulfur or sulfate can be written as:



It should be noted that the addition of reactions (6) and (7), reactions (6) and (8), reactions (6) and (9), and reactions (6) and (10) produces reaction (2), (3), (4) and (5), respectively. Therefore, Eqs. (2)–(5) are the overall reactions occurring in the system whether or not ferric ions are involved in the leaching. In practice, it is difficult to determine to which extent the indirect leaching mechanism would affect the pressure leaching rate of iron containing sulfide mixtures.

Recently, Padilla et al. (2007) have studied the pressure leaching of sulfidized chalcopyrite in sulfuric acid–oxygen system at low temperatures (90 to 120 °C) and 5 to 15 atm of oxygen partial pressure. They found that the copper dissolution from sulfidized particles increased with temperature up to 108 °C, and further increase to 120 °C decreased the copper dissolution. This decrease in copper dissolution at this temperature range was attributed to the formation of a liquid sulfur layer covering the particle's surface, which inhibited the copper dissolution.

In the present work, experimental results on the pressure leaching of sulfidized chalcopyrite in sulfuric acid–oxygen in the medium temperature range 125 to 150 °C are presented. The main objective was the determination of the kinetics of copper dissolution.

2. Experimental work

Flotation chalcopyrite concentrate was obtained from Andina Mine of CODELCO, Chile. This concentrate was classified by sieving into narrow size fractions. Table 1 and Table 2 show the chemical and mineralogical analysis of the $-53+45 \mu\text{m}$ size fraction (average size $49 \mu\text{m}$) which was used in most of the experimental work.

2.1. Sulfidation of the concentrate

The chalcopyrite concentrate was sulfidized for the leaching experiments by treating it with gaseous sulfur at 375 °C for 90 min according to the methodology described by Padilla et al. (2003a,b c). The sulfidation conversion calculated considering the weight gain of the samples according to the stoichiometry of reaction (1) was 97% for the size fraction $-53+45 \mu\text{m}$, and the calculated copper and iron content of the sulfidized material was 24% and 24.6%, respectively. X-ray diffraction analysis of the sulfidized samples indicated the formation of covellite and pyrite phases out of chalcopyrite. These results are illustrated in Fig. 1 which shows X-ray diffraction patterns of untreated chalcopyrite concentrate and a sulfidized chalcopyrite sample. We can observe in this figure that the XRD pattern for the chalcopyrite concentrate shows also diffraction picks for

Table 1
Chemical analysis of chalcopyrite concentrate of size fraction $-53+45 \mu\text{m}$

Element	Weight percent, %
Cu	27.1
Fe	27.8
S	35.8

Table 2
Mineralogical composition of the chalcopyrite concentrate

Species	Weight percent, %
Chalcopyrite	80.4
Pyrite	10.8
Bornite	0.2
Covellite	0.8
Tetrahedrite	0.6
Molybdenite	1.1
Sphalerite	0.1
Enargite	0.6
Magnetite	0.6
Gangue	4.8

molybdenite, pyrite and quartz in addition to the main picks for chalcopyrite. On the other hand, in the XRD pattern for the sulfidized material, the main peaks are for covellite and pyrite, which are the phases produced from chalcopyrite sulfidation. We can also notice the strong molybdenite peak in the sulfidized sample, which remains unchanged in this sulfidation reaction system. The absence of chalcopyrite peaks in the lower pattern suggests nearly complete conversion of chalcopyrite.

Alternatively, Fig. 2 shows a backscattered electron image (BEI) of a sulfidized sample which clearly shows the morphology of the covellite and pyrite phases formed during the sulfidation reaction. This image confirms the conclusions from the X-ray diffraction analysis that sulfidation occurs according to reaction (1). It is interesting to note that in all observed samples in this study and previous studies (Padilla et al., 2003a,b), the covellite phase forms as an outer layer surrounding a porous pyrite phase. This morphology of the sulfidized chalcopyrite particles has been explained by an electrochemical mechanism of reaction which involves simultaneous diffusion of Cu^+ and electrons through the defect structure of the FeS_2 and CuS product layers toward the surface of the particles, where the reaction of Cu^+ with $\text{S}_2(\text{g})$ takes place (Padilla et al., 2003b). A primary pyrite particle initially present in the chalcopyrite concentrate is also shown in Fig. 2. It can be

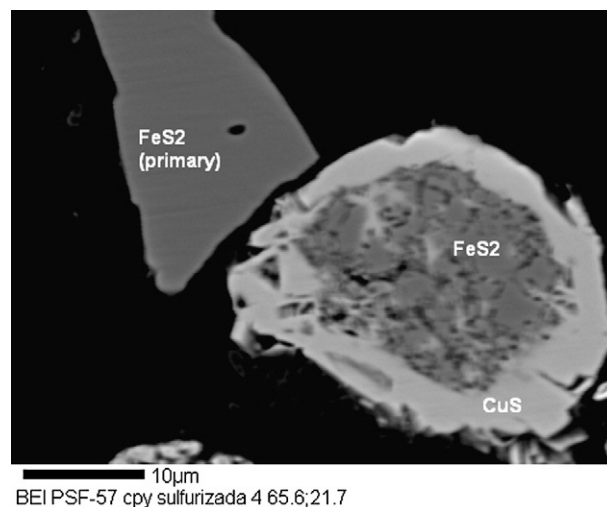


Fig. 2. Backscattered electron image of sulfidized chalcopyrite showing the peculiar morphology of the covellite phase surrounding the formed porous pyrite phase. A primary dense pyrite particle is also shown in the figure.

seen that this primary pyrite is a very dense particle in contrast to the pyrite formed by sulfidation from the chalcopyrite, which is very porous due to the large difference in molar volume between pyrite (23.9 cm^3) and chalcopyrite (43.7 cm^3).

2.2. Leaching procedure

Leaching of the sulfidized chalcopyrite samples was conducted in a 1.5 L Parr titanium autoclave. This autoclave was equipped with a heating mantle, a PID temperature controller, a variable speed stirrer with two axial impellers, and an internally mounted cooling coil. All the experiments were carried out batch-wise using 2 g of sulfidized material, 1000 ml of acid leaching solution and pure oxygen. The procedure consisted on heating the solution to 95°C ; once at this temperature, the solid sample was added and the system was further heated to the set temperature for the experiment. At

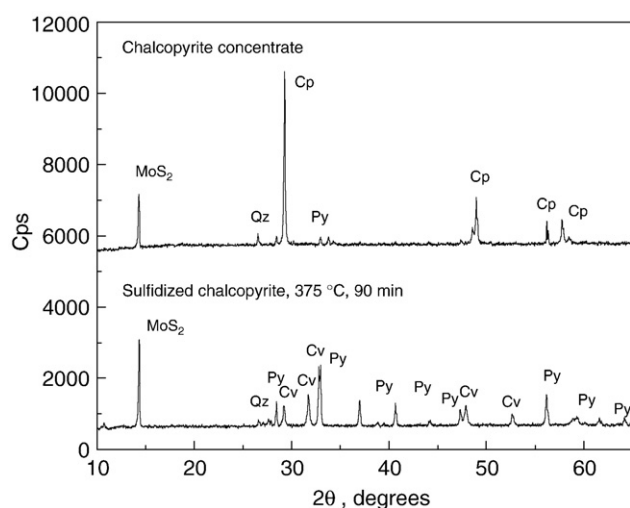


Fig. 1. X-Ray diffraction patterns ($\text{CuK}\alpha$, Ni filter) of chalcopyrite concentrate and chalcopyrite sulfidized at 375°C , for 90 min.

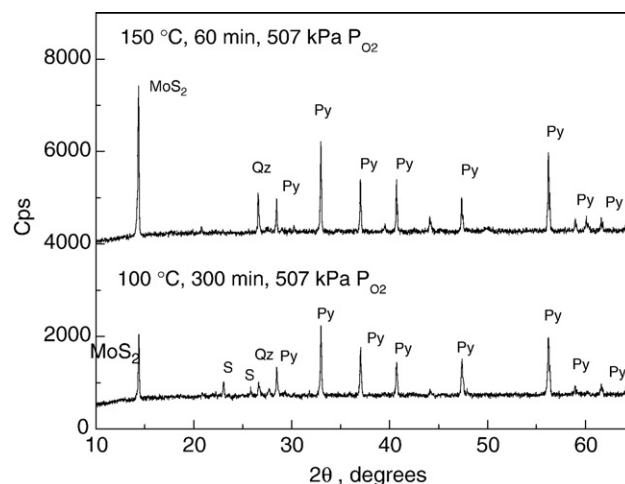


Fig. 3. XRD patterns ($\text{CuK}\alpha$, Ni filter) of two solid residues, which were obtained in leaching sulfidized chalcopyrite at the experimental conditions shown in the figure.

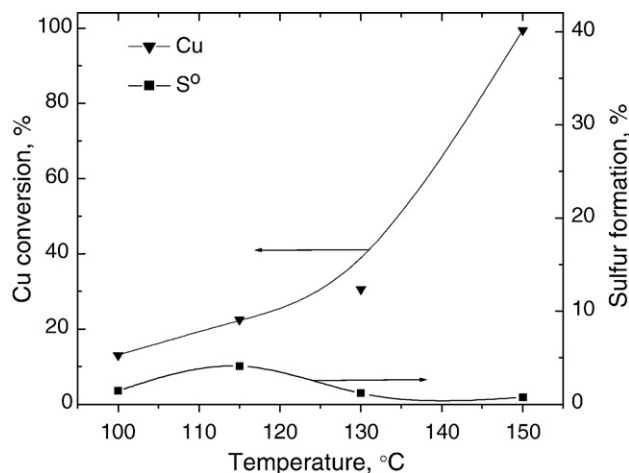


Fig. 4. Production of elemental sulfur as a function of temperature in leaching of sulfidized chalcopyrite for 60 min at 507 kPa of partial pressure of oxygen.

the set temperature, the oxygen was admitted and the partial pressure of oxygen was adjusted to the desired value, and the experiment was run for the preset time. At the end of the experiment, the autoclave was rapidly water cooled and the solution filtered for collecting the solid residues. The solution was analyzed for Cu and Fe by atomic absorption spectroscopy and the solid residues, in some cases, were analyzed by scanning electron microscopy and light microscopy. Additionally, the solid residues of some experiments were also analyzed for elemental sulfur by the Soxhlet extraction method, which is a gravimetric method where the elemental sulfur is extracted from the sample using carbon disulfide as the solvent.

3. Results and discussion

3.1. Leaching products

According to the leaching reaction (2), the solid residues from leaching should contain elemental sulfur. Solid residues from leaching at various temperatures were analyzed by XRD in order to determine the formation of elemental sulfur as a reaction product. Fig. 3 shows the diffraction

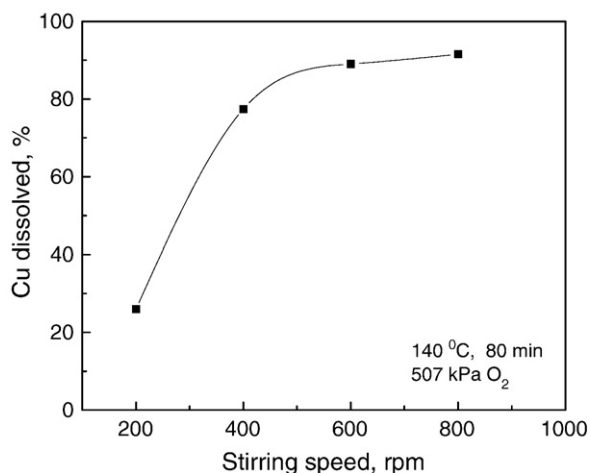


Fig. 5. Copper dissolution from sulfidized chalcopyrite as a function of stirring speed.

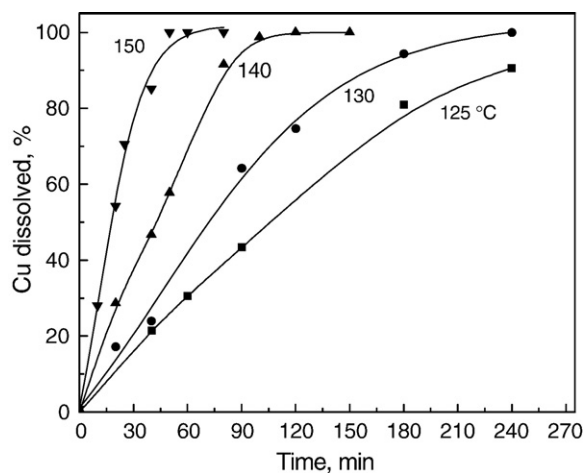


Fig. 6. Effect of temperature on the copper dissolution rate from sulfidized chalcopyrite concentrate in the range 125 to 150 °C. Conditions: 800 rpm, 0.2 M H₂SO₄, and 507 kPa partial pressure of oxygen.

patterns of two residues obtained at 100 °C, 300 min, and 150 °C, 60 min. In both experiments the partial pressure of oxygen was kept at 507 kPa and the copper dissolution was over 96%. We can observe in this figure that the residue obtained at 100 °C shows diffraction lines for elemental sulfur, and conversely, at the higher temperature of 150 °C, the sulfur lines are missing indicating that at this temperature the sulfur from the covellite was oxidized essentially to sulfate. In addition, diffraction lines for the main impurities molybdenite and quartz were present in all the XRD patterns for leaching residues. The primary pyrite was always identified in the microscopic analysis of the samples.

Fig. 4 shows the results of elemental sulfur analysis of the solid residues obtained from leaching at various temperatures for 60 min and 507 kPa of oxygen pressures. We can observe in this figure that at temperatures below 120 °C, elemental sulfur was produced, while at higher temperatures (>120 °C) the leaching occurred mainly by oxidizing the sulfur in the covellite to sulfate according to reaction (3). The latter explains why in the temperature range 125 to 150 °C studied in this research, the passivation of the leaching reaction that was observed previously at temperatures around the melting point of sulfur (Padilla et al., 2007) did not take place. We can also observe that at temperatures lower than 120 °C, the dissolution of copper in 60 min was less than

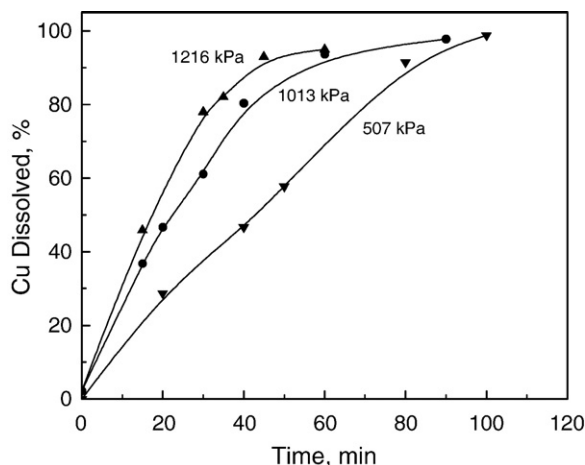


Fig. 7. Effect of partial pressure of oxygen on the dissolution of copper from the sulfidized chalcopyrite concentrates. Conditions: 140 °C, 800 rpm, and 0.2 M H₂SO₄.

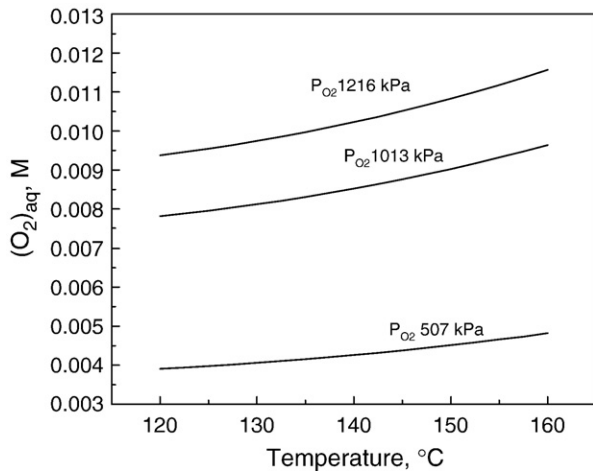


Fig. 8. Oxygen solubility in the leaching solution for various temperatures and partial pressures of oxygen according to the correlation of Tromans.

20% whereas the dissolution of copper at 150 $^{\circ}C$ for the same time was nearly 100%.

3.2. Effect of agitation on the leaching rate

The influence of stirring speed on the dissolution of copper from the sulfidized chalcopyrite was studied in experiments conducted at 140 $^{\circ}C$, 507 kPa of partial pressure of oxygen and 80 min of leaching time. The results are shown in Fig. 5.

It is evident from Fig. 5 that at 600 rpm and above there was an adequate suspension of the solid particles and adequate distribution of oxygen. Thus 800 rpm was chosen for the subsequent experiments to eliminate the stirring speed as a variable in the rate study. However, the elimination of the stirring speed as a variable does not imply that diffusion could not be a rate controlling step; it only means that with the high stirring speed the hydrodynamic boundary layer around the particles has reached a limiting value. Thus, diffusion across this minimum thickness boundary layer could still be the slow step. Therefore, additional experimental evidence (such as the value of the activation energy) is needed to ascertain the rate controlling step.

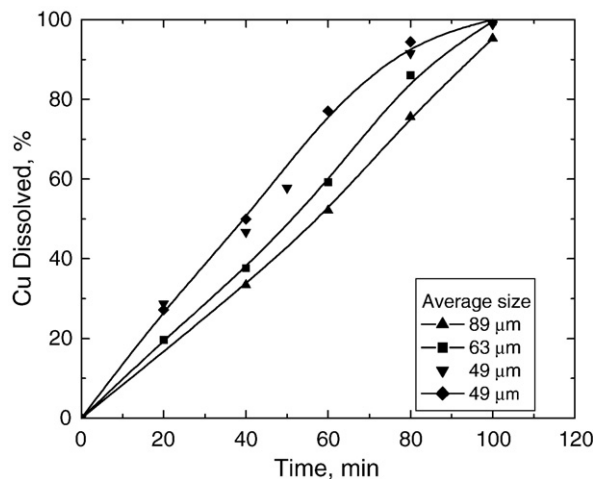


Fig. 9. Effect of particle size on the leaching of a sulfidized chalcopyrite at 140 $^{\circ}C$, and 507 kPa of partial pressure of oxygen.

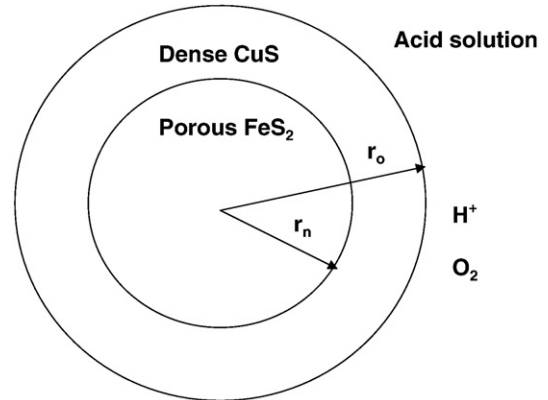


Fig. 10. Schematic representation of a sulfidized chalcopyrite particle showing the covellite and pyrite separate phases.

3.3. Effect of temperature on the leaching rate

The effect of temperature on the leaching was studied in the range 125 to 150 $^{\circ}C$ because in this medium temperature range copper is dissolved at rates of industrial interest. The results are shown in Fig. 6, where we can observe that temperature has a large effect on the copper dissolution rate. We can also observe a very fast dissolution rate at 150 $^{\circ}C$ with complete dissolution of copper in about 45 min.

3.4. Effect of partial pressure of oxygen on the leaching rate

The effect of oxygen partial pressure on the copper dissolution at 140 $^{\circ}C$ is illustrated in Fig. 7. We can observe in this figure that by increasing the partial pressure of oxygen from 507 to 1216 kPa a significant increase on the rate of copper dissolution was obtained. We can also observe that at the higher oxygen partial pressure (1216 kPa), over 90% of copper can be dissolved in less than 45 min of leaching.

Since oxygen is the main oxidizing reagent in the leaching of the sulfidized chalcopyrite, knowledge of the values of the saturation solubility of oxygen in the leaching solution is of primary interest. Therefore, the molal solubility of oxygen in a 0.2 M sulfuric acid solution for various temperatures and partial pressures of oxygen was estimated using the correlation developed by Tromans (1998). The results are shown in Fig. 8.

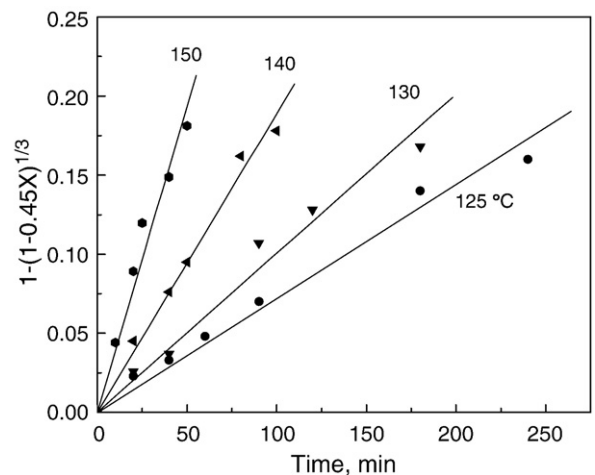


Fig. 11. Linear fit of $1 - (1 - 0.45X)^{1/3}$ versus t for the dissolution of copper from sulfidized chalcopyrite.

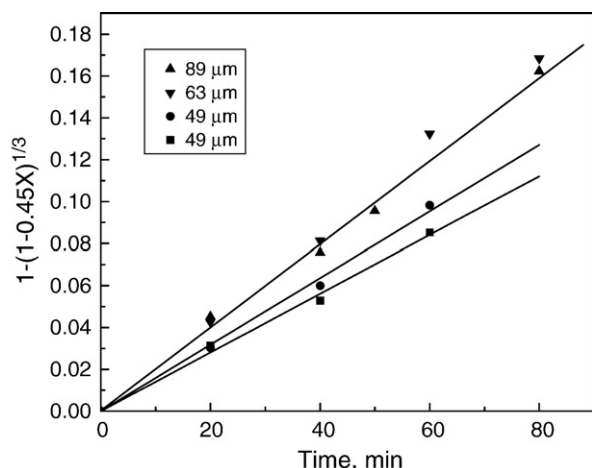


Fig. 12. Leaching kinetics of sulfidized chalcopyrite as a function of particle size. Experiments conducted at 140 °C and 507 kPa of partial pressure of oxygen.

As we can see in this figure the oxygen solubility increases somewhat between 125 and 150 °C. The effect of oxygen partial pressure on the solubility is more pronounced as expected since it is directly proportional to the partial pressure. It must be noted that for the pressure range studied in this research, the concentration of oxygen in solution is not low since it varies from about 0.004 to 0.011 M while the copper concentration varies from 0 to 0.0076 M for the low solid/liquid ratio used in this study.

3.5. Influence of particle size on the leaching rate

The influence of particle size on the leaching rate is shown in Fig. 9. This figure shows data for three average particle sizes: 49, 63 and 89 μm. The leaching conditions were 0.2 M H₂SO₄, 507 kPa of partial pressure of oxygen and 140 °C of leaching temperature. We can observe that, as expected, the smaller the size of the particles the faster the leaching rate. However, for this particle size range the effect is not very large.

3.6. Kinetics of copper dissolution from sulfidized chalcopyrite

The appreciable effect of temperature on the copper dissolution from the sulfidized concentrate suggests that this process is surface

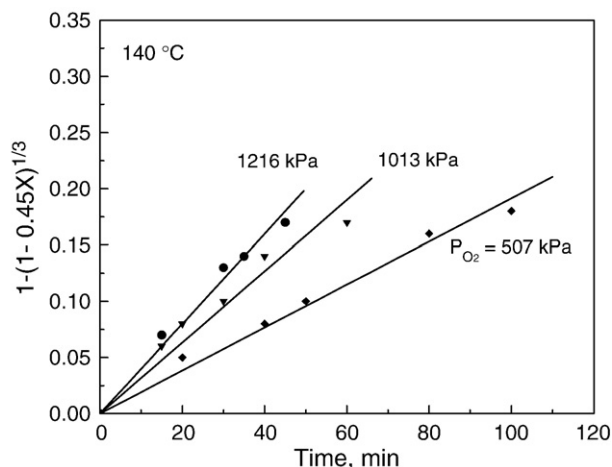


Fig. 13. Leaching kinetics of sulfidized chalcopyrite as a function of partial pressure of oxygen. Experiments conducted at 140 °C, 800 rpm, and 0.2 M H₂SO₄.

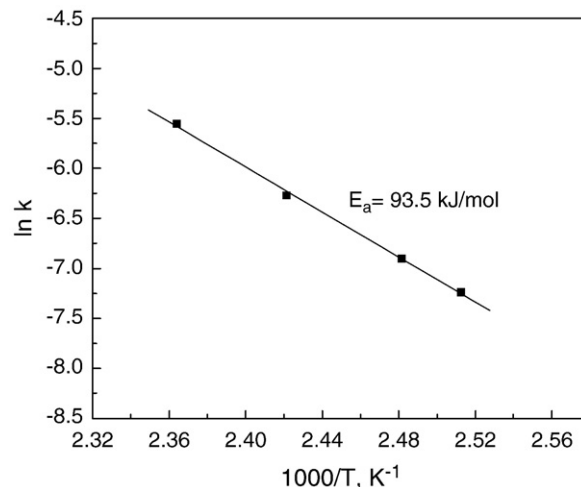


Fig. 14. Arrhenius plot for the copper dissolution from sulfidized chalcopyrite concentrate.

reaction controlled. Considering the morphology of the sulfidized particles, as seen in Fig. 2, the experimental data was analyzed by using a modified shrinking core model, which was firstly used by Padilla et al. (2003c) for the leaching of sulfidized chalcopyrite particles in H₂SO₄–NaCl–O₂ system. Essentially, this model considers the initial particle of sulfidized chalcopyrite as composed of a porous pyrite phase (FeS₂) surrounded by a dense layer of covellite (CuS). Schematically, the initial particle was represented as shown in Fig. 10 for the case of spherical geometry. Thus the dissolution of the outer rim of the sulfidized particle was analyzed by using this modified shrinking core model given as:

$$1 - \left[1 - \left(1 - \left(\frac{r_n}{r_o} \right)^3 \right) X \right]^{1/3} = kt \quad (11)$$

Where X is the fraction reacted, k is the apparent kinetic constant, t is the leaching time and r_o and r_n are the radius indicated in Fig. 10. It is worthy of noticing that when the radius of the pyrite phase, r_n , is zero Eq. (11) simplifies to the well known shrinking core model for spherical particles.

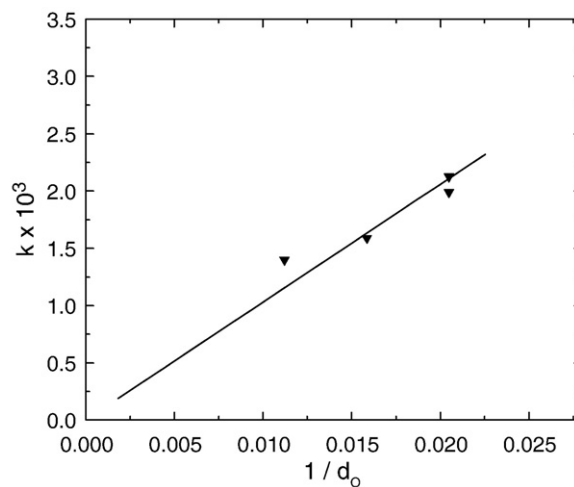


Fig. 15. Particle size dependency of the kinetic constant on the leaching of sulfidized chalcopyrite concentrates at 140 °C and 507 kPa of oxygen partial pressure.

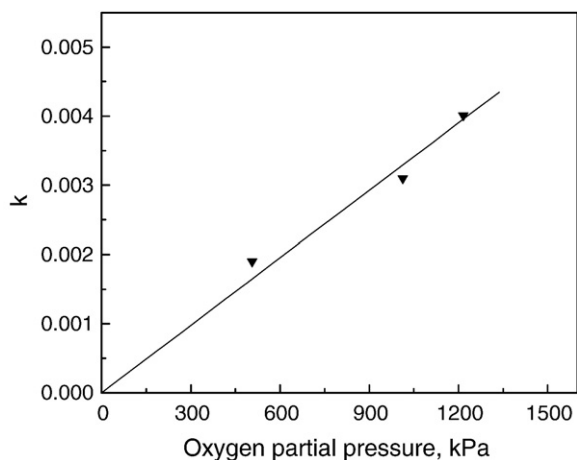


Fig. 16. Oxygen partial pressure dependency of the kinetic constant on the leaching of sulfidized chalcopyrite concentrates.

By using the experimental value of 0.82 for the ratio r_n/r_o determined for the sulfidized chalcopyrite (Padilla et al., 2003c) the model reduces to:

$$1 - (1 - 0.45X)^{1/3} = kt \quad (12)$$

The apparent kinetics constant k is a function of the partial pressure of oxygen and the initial diameter of the particle, d_o , given as follows:

$$k = k' \frac{P_{O_2}^m}{d_o} \quad (13)$$

where m is the reaction order with respect to the partial pressure of oxygen and k' is a kinetic constant that depends on the temperature.

The experimental results for various conditions plotted according to Eq. (12) are shown in Figs. 11, 12 and 13, where we can observe that the model fits the data well. From the slope of the curves in Fig. 11, the apparent kinetic constants for the various temperatures can be determined, which were used to draw an Arrhenius plot as shown in Fig. 14. The calculated activation energy was 93.5 kJ/mol, which is a typical value for a process controlled by surface chemical reaction. This kinetic model for the copper dissolution is additionally supported by the good linear dependency of the experimental kinetic constant on the inverse of the initial particle

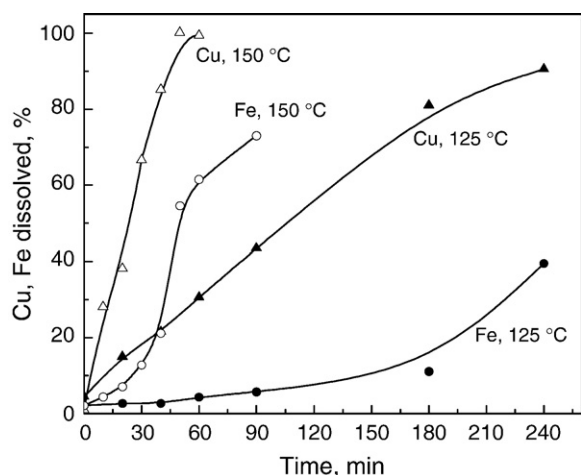


Fig. 17. Iron dissolution from sulfidized chalcopyrite concentrate as compared to the dissolution of copper at temperatures 125 and 150 °C, and partial pressure of oxygen 507 kPa.

size, as shown in Fig. 15. This result confirms that the leaching proceeds according to Eq. (12).

The dependence of the kinetic constant on the partial pressure of oxygen can also be determined from the slopes of Fig. 13. Fig. 16 shows a plot of $\ln k$ versus $\ln P_{O_2}$ where one can see a straight line passing through the origin; this result indicates that the rate of dissolution of copper from sulfidized chalcopyrite is first order with respect to the partial pressure of oxygen.

3.7. Iron dissolution

The results concerning the dissolution of iron from the sulfidized chalcopyrite are shown in Fig. 17, where the iron dissolution is compared to the copper dissolution at 125 °C and 150 °C. We observe in this figure that temperature has also a pronounced effect on the dissolution of iron and we can also observe that the copper/iron selectivity is good only at short reaction times. In spite of the appreciable amounts of iron dissolved at 150 °C, the pressure leaching of sulfidized chalcopyrite is still a viable option because of the fast copper dissolution rates.

4. Conclusions

From the experimental results on the leaching of sulfidized chalcopyrite the following can be concluded.

A stirring speed over 600 rpm was sufficient to eliminate the effect of this variable on the rate study. The pressure leaching of sulfidized chalcopyrite concentrate in the range 125 to 150 °C occurs mainly through reaction (3), with the oxidation of the sulfide sulfur to sulfate. Temperature has an important influence on the copper dissolution in the range 125 to 150 °C. The dissolution rate was very rapid at 150 °C and 507 kPa (5 atm). Copper was completely dissolved from the sulfidized chalcopyrite concentrate in 45 min. Increasing the partial pressure of oxygen from 507 kPa to 1216 kPa (5 to 12 atm) at 140 °C, a significant increase on the rate of copper dissolution was obtained. At the high oxygen partial pressure of 1216 kPa (12 atm), over 90% of copper can be dissolved in less than 45 min of leaching.

The kinetics was analyzed by using the shrinking rim model: $1 - (1 - 0.45X)^{1/3} = kt$, and the calculated activation energy was 93.5 kJ/mol, which is a typical value for a process controlled by surface chemical reaction. The rate of copper dissolution was found to be of first order with respect to the partial pressure of oxygen.

Acknowledgements

The authors acknowledge the National Fund for Scientific and Technological Development (FONDECYT) of Chile for the financial support of this investigation through project No.1050948.

References

- Bailey, L.K., Peters, E., 1976. Decomposition of pyrite in acids by pressure leaching and anodization: the case for an electrochemical mechanism. *Canadian Metallurgical Quarterly* 15 (4), 333–344.
- Cheng, C.H., Lawson, F., 1991. The kinetics of leaching covellite in acidic oxygenated sulphate-chloride solutions. *Hydrometallurgy* 27, 269–284.
- Dutrizac, J.E., 1982. Ferric ion leaching of chalcopyrite from different localities. *Metallurgical Transactions* 13B, 303–309.
- Gary, J.H., McEwen, R.B., Samis, A.N., 1994. The Quebrada Blanca copper project. *CIM Bulletin* 87 (1985), 35–45.

- Hackl, R.P., Dreisinger, D.B., Peters, E., King, J.A., 1995. Passivation of chalcopyrite during oxidative leaching in sulphate media. *Hydrometallurgy* 39 (1-3), 25–48.
- Jó, M., Bustos, S., Espejo, R., Ruiz, P., Rojas, J., Montealegre, R., 1991. Bacterial thin layer leaching of copper sulfide ores. *Proceedings of the CIM-IIMCH-TMS Int. Conference: Copper 91-Cobre 91*, Ottawa, Canada, CIMM, pp. 87–97.
- Lotens, J.P., Wesker, E., 1987. The behaviour of sulphur in the oxidative leaching of sulphidic minerals. *Hydrometallurgy* 18, 39–54.
- Monhemius, A.J., 1996. Hydrometallurgy—the clean solution for metal production? In: *Clean Technologies for the Mining Industry. Proceedings of the III International Conference on Clean Technology for the Mining Industry*, Santiago, Chile, pp. 13–24.
- Muñoz, G., 1996. Codelco-Chile's corporate decontamination plant for its smelters. In: *Clean Technologies for the Mining Industry. Proceedings of the III International Conference on Clean Technology for the Mining Industry*, Santiago, Chile, May 1996, pp. 53–64.
- Padilla, R., Rodríguez, M., Ruiz, M.C., 2003a. Sulfidation of chalcopyrite with elemental sulfur. *Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science* 34B, 15–23.
- Padilla, R., Olivares, E., Sohn, H.Y., Ruiz, M.C., 2003b. Kinetics of the sulfidation of chalcopyrite with gaseous sulfur. *Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science* 34B, 61–68.
- Padilla, R., Zambrano, P., Ruiz, M.C., 2003c. Leaching of sulfidized chalcopyrite with H_2SO_4 – NaCl – O_2 . *Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science* 34B, 153–159.
- Padilla, R., Vega, E., Ruiz, M.C., 2007. Pressure leaching of sulfidized chalcopyrite in sulfuric acid–oxygen media. *Hydrometallurgy* 86, 80–84.
- Richmond, G., 2004. The Mount Gordon Copper Process. *Proceedings of the International Colloquium on Hydrometallurgical Processing of Copper Sulfides (Hydro-Sulfides 2004)*, April 16–19, Santiago, Chile, pp. 75–88.
- Tromans, D., 1998. Oxygen solubility in inorganic solutions: concentration, temperature and pressure effects. *Hydrometallurgy* 50, 279–296.
- Valenzuela, A., Palacios, J., Cordero, D., y Sánchez, M., 2003. The Chilean copper industry: an Update. *Metallurgical and materials processing: principles and technologies*. In: Kongoli, K., et al. (Ed.), *High Temperature Metals Production*, TMS, Warrendale, PA, USA, vol. II, pp. 239–252.