Hydrometallurgy 158 (2015) 1–9

Contents lists available at ScienceDirect

Hydrometallurgy

journal homepage: www.elsevier.com/locate/hydromet

A study of the electrochemical dissolution and passivation phenomenon of roasted gold ore in cyanide solutions

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 17 September 2015
Accepted 22 September 2015
Available online 25 September 2015

Keywords:
Gold
Roasted gold ore
Magnetite
Hematite
Passivation

ABSTRACT

This study investigates the electrochemical interactions between gold and its associated oxide minerals either in one (OC) or two separate containers (TC) in the presence or absence of slurry. Magnetite showed negative effect on gold leaching, while maghemite and hematite demonstrated positive effect, relatively. The presence of slurry generally resulted in lower current densities. However, when the tailings of slurry was used again as a new feed in two separate containers (TC), the dissolution rate of gold was increased by 3 times (30 to 90 μA cm^{-2}), suggesting that the removal of detrimental ions in the first stage. Moreover, the current density of gold was enhanced up to 10 times by magnetic pre-treatment of roasted gold ore. It was found that in cyanide solutions saturated with atmospheric oxygen, cathodic Tafel slope only ($8.60 \times 10^{-7} \pm 4.56\%$ mol m^{-2} s^{-1}) provides close corrosion rates of gold to that in practical cyanidation ($10.57 \times 10^{-7} \pm 1.33\%$ mol m^{-2} s^{-1}), suggesting that cathodic polarization is the rate controlling one. Furthermore, a new electrode consisted of equal quantities of magnetite and hematite in one electrode was developed to examine the influence of these two major iron oxides on gold leaching, concurrently 0.04 M NaCN at 100 rpm agitation was found to be optimal. SEM analysis indicated the presence of Fe-oxide and Au–C compound products that could be responsible for partial passivation of gold surface.

1. Introduction

It has been known that cyanidation is an electrochemical corrosion process (Thompson, 1947), thus the anodic dissolution of gold can readily be studied by electrochemical techniques. In previous electrochemical studies, the dissolution rate of gold has been considered as the intersections of cathodic and anodic Tafel curves (Kudryk and Kellogg, 1954; Cerovic et al., 2005). However, Dai and Breuer (2013) have recently indicated that considering Evan's diagrams could be misleading due to inherent flaws such as oxidation half reaction which does not include the influence of oxygen. Additionally, Crundwell (2013) claimed that each point on the mineral surface is considered as both an anodic site and a cathodic site and concluded that there is no separation of anodic and cathodic sites on a mineral's surface. According to these findings, electrochemical studies of gold are still subjects of interest.

During cyanidation, the anodic dissolution of gold may be reduced/retarded in some conditions, and in that case passivation and galvanic interaction phenomena are considered as potential significant electrochemical factors (Lorenzen and van Deventer, 1992; Mrkusic and Paynter, 1970). Passivation phenomenon of gold has been known since 1907 and assumed that the passivity is due to the formation of a surface film on the surface of gold (Cathro, 1961). Passivation of gold has been linked to dissolved species, presence of impurities, gold oxide and hydroxide films, and insoluble sodium aurocyanide film (Kirk et al., 1978; Nicol, 1980; Mrkusic and Paynter, 1970).

It is assumed that gold dissolution may be influenced when gold is in contact with conductive minerals (Lorenzen and van Deventer, 1992). Aghamirian and Yen (2005) employed potentiodynamic polarization tests in one container and found that pyrite and pyrrhotite showed positive effect on the leaching of gold which is not in agreement with the previous findings of Paul (1984), and Lorenzen and van Deventer (1992). However, Filmer (1982) mentioned that gold becomes passive if it is in contact with a conductive mineral, and this was linked to the formation of a passive film on the surface of gold due to the enhanced cathodic current. Van Deventer et al. (1990), and Lorenzen and van Deventer (1992) examined the polarization of electrically connected gold and sulphide mineral electrodes either in one or two separate containers where platinum was used as a counter electrode. In the case of hematite and gold connection, identical curves were obtained in one and two containers, indicating that only galvanic interactions played a significant role in retarding the dissolution rate of gold. Azizi et al. (2010) found that gold dissolution rate in one container was lower than in two separate containers and this difference was explained

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http://dx.doi.org/10.1016/j.hydromet.2015.09.020
0304-386X/

by the partial passivation of gold surface by a resistive film of Au_2S and/or metal hydroxides releasing from mineral electrode. Then, it can be deduced that the influence of each mineral could show different effects and generalizing the influence of each mineral may not be correct in all cases and that depends on the anodic and cathodic behaviours of gold and its associated minerals.

Till now, almost all previous electrochemical studies of gold were conducted using only sulphidic gold ores (van Deventer and Lorenzen, 1987; Van Deventer et al., 1990; Lorenzen and van Deventer, 1992; Aghamirian and Yen, 2005; Cruz et al., 2005; Dai and Jeffrey, 2006; Azizi et al., 2010, 2011, 2012a, 2012b, 2013), and the influence of slurry was not systematically considered. On the other hand, there is a lack of electrochemical studies between gold and oxide minerals. Additionally, since there is an increasing trend on the treatment of refractory gold ores which often requires oxidation such as roasting prior to cyanidation (Zhou and Fleming, 2007), this subject is therefore becoming essential for the gold mining industry. Hence, the objectives of this paper are: (i) to examine the influence of oxide minerals on gold leaching. In this manner, Combined Anode Electrode Polarization "CAP" approach was developed to have a local galvanic cell; (ii) to examine/understand the dominating effect in between galvanic interactions and passivation phenomena on gold leaching either in one container (OC) or two separate containers (TC) in the absence or in the presence of slurry; and (iii) to study the effect of two major oxide minerals, concurrently, as function of cyanide concentration and agitation speed. Thus, a new electrode consisted of equal surfaces of magnetite and hematite in one electrode, named as "MagHem-ES", was developed.

2. Experimental conditions

2.1. Material and preparation of electrodes

Roasted gold ore sample (80% passing −75 μm (d_{80})) was received from Barrick Gold Corporation. Mineralogical analyses of the sample using X-ray diffraction (XRD, Siemens D-5000) and scanning electron microscopy (SEM, JEOL 840-A) indicate that the ore sample consists predominantly of quartz, dolomite, calcite, gypsum, and iron oxides such as hematite, magnetite, maghemite, and with almost non sulphur content. Microscopic analysis showed that gold is mainly associated with iron oxides. Metal analysis by atomic absorption spectroscopy (AAS, Perkin Elmer AAnalyst 800) has shown that gold and silver contents are ~8 and ~5 g/t, respectively (Bas et al., 2015a).

Sodium cyanide (NaCN) with a ≥98% purity was obtained from Thermo Fisher Scientific Company. Electrolyte medium was prepared using distilled water and pH was adjusted to 10.5 by adding 1 M NaOH. Electrolyte was agitated with a magnetic bar (4 cm long and 1 cm diameter) during tests. Pure gold (Au) disc electrode was used as a working electrode while platinum (Pt) as a counter electrode and $Ag/AgCl,KCl_{sat}$ as a reference electrode. 0.25 cm^2 of gold foil (99.9% purity from Sigma Aldrich), as pure gold electrode (Au), was first polished with a fine (MicroCut® 100 Grit Soft) polishing paper and then rinsed in distilled water. Then, it was introduced in aqua-regia for 10 s to clean the surface, washed with distilled water and ethanol and finally rinsed with distilled water again, to assure the reproducibility (Kirk et al., 1978).

Roasted gold ore (RGO), magnetite (Mag), hematite (Hem), maghemite (Mgh), and magnetite-hematite (MagHem-ES) disc electrodes with an exposed surface area of 4.9 cm^2 were used, as mineral electrodes. Maghemite was prepared by heating magnetite in oven at 200 °C for 3 h as giving a light brown colour to be maghemite (Legodi and de Waal, 2007) and this was proved by XRD (Bas et al., 2015b). MagHem-ES consisted of equal surfaces of hematite and magnetite in one electrode. In each case, roasted gold ore, magnetite, hematite, and maghemite, separately, were mixed with graphite powder (to increase the conductivity) 3:1 and with few drops of silicone oil, for binding, till a paste was obtained. Graphite powder, which has a particle size of <45 μm, and a 99% purity, was obtained from Sigma-Aldrich. The mixture was manually homogenized during 30 min, in general. Then, it was mechanically pressed at 20 tons to have uniform sample surface. After that, disc electrodes were kept under nitrogen atmosphere over a night. Then, these electrodes connected with an insulated copper wire, cast in acrylic resin.

2.2. Electrochemical test procedures

First, electrodes were allowed to stay at open circuit potential (OCP) for 2 min before linear polarization tests with a range of ±25 mV with respect to corrosion potential (E_{corr}). Actually, different stabilization times (up to 30 min) were also considered, however the reproducibility was ±4%. Then, cathodic polarization tests were performed by scanning from E_{corr} to −300 mV and corrosion current (i_{corr}) was estimated by considering the cathodic Tafel slope only extrapolating to OCP. Anodic polarization tests were performed by scanning from E_{corr} to +1000 mV. Tests were performed generally in 0.01 M NaCN electrolyte at pH 10.5 at 100 rpm magnetic agitation at room temperature, saturated with atmospheric oxygen, unless otherwise reported. Scan rate of 0.166 mV/s was selected based on the polarization standards (ASTM Standard G 5-94, 2006). Corrosion rates of gold by Tafel were compared to cyanide leaching results. In case of cyanide leaching tests, leach solution was prepared using deionized-distilled water at the prescribed concentration of reagent and leached during 3 h. During the experiments, pH was maintained at 10.5 by the addition of 1 M NaOH. Solution was sampled at predetermined intervals and analyzed by atomic absorption spectrophotometer (Atomic Absorption Spectroscopy, AAS - Perkin Elmer AAnalyst 800) to determine the gold leaching rate. Electrochemical tests were performed at least in triplicates to assure the reproducibility. In case of slurry tests, to simulate the practical conditions, 35% solid ratio as a slurry of roasted gold ore was considered.

Combined anode electrode polarization "CAP" approach tests, where gold and mineral disc electrodes were electrically connected to each other as anode to establish a local galvanic cell, were performed either in one container (OC) (Fig. 1) or two separate containers (TC). Platinum as a counter electrode and $Ag/AgCl,KCl_{sat}$ as a reference electrode (0.199 V/SHE) were used and all potentials here were reported vs. standard hydrogen electrode (SHE). In case of two separate containers (TC) tests, mineral electrode (having as its open circuit potential) was placed into one of the containers and it was electrically connected with Au electrode in the other container (that contains platinum as counter electrode) to have a "Au anode connected to non-polarized mineral electrode". The potential of mineral electrode was measured with a separate reference electrode (SHE) in case of two separate containers tests. In certain experiments for comparison, another platinum electrode was also put in the cell of mineral electrode and that was electrically connected to other platinum electrode in the cell of Au to have a "polarized Au-mineral electrode". Surface characterization tests were carried out on scanning electron microscopy (SEM) (JEOL 840-A) coupled with Energy-Dispersive X-ray Spectroscopy (EDS).

3. Results and discussion

3.1. Potentiodynamic cathodic polarization of gold and roasted gold ore

Fig. 2a and b shows the influence of oxygen and cyanide on cathodic polarization profiles of pure gold and roasted gold ore electrodes, respectively, by scanning from E_{corr} to −300 mV at pH 10.5 at 100 rpm agitation in 0.01 M NaCN electrolyte. In the presence of cyanide and atmospheric oxygen, the dissolution potential of pure gold was found to be at ~−550 mV (Fig. 2a). To examine the influence atmospheric oxygen on cathodic polarization of gold, bubbling N_2 prior and during the tests was considered. Almost same trends were observed