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Electrochemical Dissolution of Roasted Gold Ore in Cyanide Solutions

Ahmet Deniz Bas\textsuperscript{1*}, Liliana Gavril\textsuperscript{1}, Wei Zhang\textsuperscript{1}, Edward Ghali\textsuperscript{1} and Yeonuk Choi\textsuperscript{2}

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Abstract

In free corrosion tests, pure gold (Au) electrode gave more active behaviour than that of roasted gold ore (RGO) electrode. Electrochemical noise measurements of Au electrode generally showed an increasing trend in corrosion rate, while RGO plateaued after initial 10 h until 24 h. Scanning reference electrode technique, at open circuit potential, showed higher quasi electromotive force for Au than RGO electrode. Optimal leaching conditions for RGO were found to be 0.04 M NaCN concentration, pH 10-10.5, and 250 rpm agitation speed. It was found that in cyanide solutions saturated with atmospheric oxygen, cathodic Tafel slope only (3.30 \times 10^{-8} \pm 3.27\% \text{ mol m}^{-2} \text{s}^{-1}) provides representative corrosion rates of gold for RGO to that in practical cyanidation (3.07 \times 10^{-8} \pm 7.03\% \text{ mol m}^{-2} \text{s}^{-1}). Considering the anodic curve for Tafel slope or Stern-Geary methods was found to be misleading due to the presence of different constituents. The cathodic reaction on few sites of metallic conductive phase is the rate controlling one. Potentiodynamic scanning of cathodic polarisation curve should go directly without cathodic cleaning from corrosion potential to more cathodic ones for both Au and RGO electrodes. SEM analysis indicated the presence of Fe-oxide products could be the main contributor to the passivation of the gold surface.

Keywords: Roasted gold ore, corrosion rate, passivation, cathodic Tafel, cyanidation

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1. Introduction

During cyanidation, leaching of gold is reduced or retarded in some conditions. Since cyanidation is an electrochemical based process (Habashi, 2009), thus dissolution of gold can be readily studied by electrochemical techniques. Recently, 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. Habashi and Bas (2014) pointed out that certain experimental results demonstrated the existence of anodic and cathodic zones during the dissolution of minerals. These findings have revealed that electrochemical studies of gold still receive much attention.

Passivation of gold, diffusion control, and galvanic interactions are considered as important factors affecting the leaching of gold (Filmer, 1982; Azizi et al., 2011). Passivation of gold has been known since 1907 and gold becomes passive under certain conditions in commercial cyanide solution and assumed that the passivity is due to the formation of insoluble sodium aurocyanide film on the surface of gold (Cathro, 1961). Mrkusic and Paynter (1970) identified the passivation as the film formation of dissolved species from calcine while Nicol (1980) reported that passivation of gold mainly depends on the presence of impurities in the solution. It was suggested that gold oxides and cyanide films are responsible for the passivation of the surface of gold (Kirk et al., 1978). The different types of dissolved minerals found in the ore may have positive and/or negative effect on the rate of gold dissolution (Jeffrey and Ritchie, 2001; Nicol, 1980).

Although many studies have been carried out, there is still a doubt on gold passive phenomenon.

In the present time, it is well known worldwide that there is an increasing trend on the treatment of refractory ores (often requires oxidation prior to cyanidation) due to the rapid depletion in free-milling gold ores (Zhou and Fleming, 2007). 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 1992a and 1992b; Aghamirian and Yen, 2005; Cruz et al., 2005; Dai and Jeffrey, 2006;
Azizi et al., 2010, 2011, 2012a, 2012b, 2013). On the other hand, there is a paucity on electrochemical interaction studies between gold and its oxide minerals. At the same time, the influence of agitation was not systematically considered in previous studies. Therefore, an increasing request of the gold mining industry for this issue is created. Furthermore, the corrosion (dissolution) rate of gold was considered from the intersections of anodic and cathodic Tafel slopes (Cerovic et al., 2005). However, Dai and Breuer (2013) showed that using only Evans’ diagrams is misleading for gold dissolution estimation. These findings indicate that calculation of corrosion rate of gold is still an important issue.

Based on the above statements, the main objective of this study is to provide a detailed understanding of electrochemical behaviour and optimal leaching conditions (NaCN concentration, pH, and agitation speed) for roasted (oxidized) gold ore, as far as possible, by using conventional and more recent electrochemical techniques such as Electrochemical Noise Measurement (ENM) and Scanning Reference Electrode Technique (SRET). ENM is referred to as a random fluctuation of current and/or potentials that has received widely attention to study the electrochemical systems (Eden, 2011) and is used for monitoring active and passive behaviours, and type of corrosion of tested specimen (Lafront et al., 2010; Safizadeh and Ghali, 2013). Although the majority of ENM studies have been carried out in corrosion studies, there is a recent attempt using ENM in leaching studies (Bevilaqua et al., 2006). This method could potentially be an alternative in gold leaching studies for the characterization of surface products that could lead to surface passivation. SRET was considered to contribute to the electrochemical dissolution of gold since SRET in-situ provides significant information on anodic and cathodic potentials of a specimen as a function of time in free corrosion mode (Zhang et al., 2006). It is also possible to analyse the active and passive behaviours of gold with the 3D image facility of SRET. Furthermore, electromotive force of the corrosion cell is calculated by the evaluation of SRET data. This study also investigates the corrosion rate of gold by cathodic Tafel slope, Stern-Geary method, and compared to that obtained by conventional cyanidation. Concurrently, providing an appropriate understanding on the passivation phenomenon of gold is also one of the objectives.
2. Experimental conditions

2.1. Roasted gold ore sample

The gold ore sample was obtained from Barrick Gold Corp. This was the calcine after roasting of refractory gold ore. The sample (which was already reduced in size 80% passing -75 µm (d<sub>80</sub>)) was riffled as portions prior to use in experiments.

Mineralogical analysis of the sample indicates that the ore sample consists predominantly of quartz, dolomite, calcite, gypsum, and iron oxides such as hematite, magnetite, and maghemite and with almost non sulphur content. Gold is mostly associated with iron oxides. Metal analysis of the ore sample by AAS for Au and Ag after hot aqua regia digestion has shown that gold and silver contents are ~8 and ~ 5 g/t, respectively.

2.2. Material and preparation of electrodes

NaCN (≥98% purity) was obtained from Thermo Fisher Scientific Company. Electrolyte medium (1L) was prepared using distilled water and pH was adjusted at 10.5 by adding 1 M NaOH. Electrolyte was magnetically agitated (4 cm long and 1 cm diameter) during the tests. Pure gold (Au), rotating disc (RDE), roasted gold ore (RGO) and its oxide electrodes magnetite (Mag), and hematite (Hem) disc electrodes were used as working electrode while platinum (Pt) as a counter electrode and Ag/AgCl/KCl sat as reference electrode.

1 cm<sup>2</sup> of gold foil (99.9% purity from Sigma Aldrich), as pure gold electrode (Au), was first polished with fine (MicroCut® 100 Grit Soft) polishing paper and then rinsed in distilled water. Then, it was introduced in aqua-regia for 10 seconds to clean the surface, washed with distilled water and ethanol and finally rinsed with distilled water again, to assure the reproducibility. Rotating ring disc electrode (RDE), where disc electrode was connected to a rotator, with a surface area of 0.05 cm<sup>2</sup> gold was obtained from ALS Co., Ltd. (Japan) and was used in certain tests.

Roasted gold ore (RGO), magnetite (Mag), and hematite (Hem) disc electrodes with an exposed surface area of 4.9 cm<sup>2</sup> were prepared. In each case, roasted gold ore, magnetite,
hematite were mixed with graphite powder (to increase the conductivity) 3:1 and with around 0.4 g 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 minutes, in general. Then, it was mechanically pressed at 20 tons to have uniform sample surface. After that, all disc electrodes were kept under nitrogen atmosphere over a night. The electrical contact was assured by an insulated copper wire, cast in acrylic resin. Although it is difficult to mimic the practical conditions in laboratory studies (for surface areas), due to the low quantity of gold in its ore, however, the chosen difference in surface areas of electrodes is considerably suitable to see the main tendencies and influences of minerals on gold dissolution.

2.3. Electrochemical test procedures

2.3.1 Open circuit potential (OCP)

In open circuit potential (OCP) or free corrosion potential tests, NaCN concentration was kept at 0.04 M and tests were carried out in 400 mL beakers. Dissolution potential of gold may be influenced either in a positive or negative way due to the presence of soluble ions in the solution. Therefore, to monitor the changes in open circuit (dissolution) potential of gold and roasted gold ore electrodes as function of soluble species, the addition of slurry into the solution was considered to mimic the real leaching conditions. When the tests were conducted in presence of roasted gold ore the solid ratio was adjusted at 35% wt/vol. All the tests were conducted for 24 h. In the case of RDE the electrode was monitored for the first hour. After that, RDE was taken off from the solution and kept under N₂ conditions for the next 22 h to prevent its corrosion. During this period the solution was continually magnetically agitated (100 rpm). After 22 h (23 h since the beginning of experiment), the RDE was again placed into the solution without any change in the potential for 1 h to complete 24 h in total.
2.3.2 Electrochemical noise measurement (ENM)

Prior to electrochemical noise measurement (ENM) tests, two working electrodes were prepared separately following the three steps: cathodic cleaning for 50 min. and potentiodynamic polarization (-0.8 to 1.2 V) and then potentiostatic measurement (at 1 V) for 2 h. The Electrochemical noise measurements were performed in employing a set-up using zero resistance ammeter (ZRA) mode in 0.04 M NaCN solution. In this mode, the electrochemical noise could be measured between two nominally identical working electrodes as the galvanic coupling kept at the same potential. The samples were immersed in the solution where the system was allowed to stand at open circuit for 5 min. Then, the potential and current fluctuations were simultaneously recorded during 24 hours at a scan rate of f_s=10 Hz. This scan rate is generally preferred since it is quite enough to have a clear trend in noise data. If a more precise of noise data is requested, then a higher scan rate could be applied, however, the general trend will be same and this does not affect to the noise resistance, in overall. All potentials were measured vs. Ag, AgCl/KCl saturated reference electrode (0.199 V), and reported with respect to Standard Hydrogen Electrode (SHE).

The ENM tests were carried out without agitation and exposed to atmospheric oxygen. A Gamry® PC4/300 potentiostat was used to log current and potential variations in time. The analyses were performed using a GAMRY® PC4 750/ESA400 software and analyser v. 2.35. The DC drift was removed before all analyses to eliminate the trend. At least, three series of tests were performed for each examined sample.

2.3.3 Scanning reference electrode technique (SRET) procedure

Au and roasted gold ore electrodes were mounted horizontally in the cell of SRET apparatus (EG&G Instruments-Model SVP100) for free corrosion potential measurement (Fig. 1). After ensuring that the surface of the specimen was parallel to the surface on the Perspex tripod and leveled, the probe was lowered to a distance of 100 µm above the sample surface, and then the cyanide solution was added. The basic configuration is to connect one input (+ve) to the vibrating probe and the other input (-ve) to a separate
reference probe (carbon electrode in this case) placed in the solution local to the surface to be measured. After conditioning of the signal, a rectangular area (18.0 mm by 13.5 mm) was scanned, overlapping slightly the acrylic resin. The vibrating probe amplitude was adjusted at 45 µm, and the data collection was scanned at 32 points per scan line on X-axis and for a total of 24 lines on Y-axis. For each data point, 500 potential measurements were taken at a frequency of 81 Hz. Each SVP scan lasted approximately 19 min and 1 min of rest was allocated between each scan, all the experiments were conducted over a period of 16 hours. The overall SRET data were used to reproduce a three-dimensional image mapping of the surface potential over the specimen. Referring to this 3-D image map, the down cones (↓) correspond to anodic potentials (inside pits) and the up cones (↑) represent the cathodic potentials (Zhang et al., 2006).

![Schematic illustration of Scanning Reference Electrode Technique (SRET) set-up](image)

**Fig. 1** Schematic illustration of Scanning Reference Electrode Technique (SRET) set-up (CE: counter electrode; RE: reference electrode; WE: working electrode)

2.3.4 *Linear and potentiodynamic polarization*

Corrosion current by cathodic Tafel polarization results were performed and compared to that of obtained from linear polarization by using Stern-Geary method. First, electrodes were allowed to stay at open circuit potential for 2 minutes before linear polarization tests for corrosion rates with a range of ±25 mV with respect to corrosion potential (E_{corr}). Actually, different stabilization times (up to 30 minutes) were also considered, however the difference (only up to ±5%) was found to be negligible. Then, cathodic polarization tests by scanning from E_{corr} to -300 mV were performed to calculate also the corrosion
current ($i_{corr}$), considering cathodic Tafel slope only. Tests were performed generally in 0.04 M NaCN electrolyte at pH 10.5 at 100 rpm magnetic agitation (4 cm long and 1 cm diameter) at room temperature, saturated with atmospheric oxygen and 0.166 mV/s scan rate, considering polarization standards (ASTM Standard G 5-94, 2006). Each test was carried out at least in triplicates to assure the reproducibility. To simulate the practical conditions, polarization tests with the same procedure was also carried out in the presence of slurry (35 % solid ratio).

2.4. Conventional cyanide leaching

Leach solutions were prepared using deionised-distilled water at the prescribed concentration of reagents (0.04 M NaCN). Leaching tests were conducted at 250 rpm agitation speed for 24 h in 0.48 L solutions into which roasted gold ore disc electrode (4.9 cm$^2$) was placed. 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 Analyst 800) to determine the gold leaching rate.

3. Results and discussion

3.1 Dissolution behaviour of gold at open circuit potentials (OCP)

3.1.1 OCP studies of disc electrodes as function of slurry

Open circuit potential also known as free corrosion potential is critical in electrochemical tests since open circuit potential ($E_{corr}$) provides significant information about the corrosion behaviour of each mineral or metal, also it is important for galvanic interactions. Preliminary tests have confirmed that 100 rpm agitation could be suitably used for open circuit potential tests at 25 °C. This is supported by the work of Sheveleva and Kakovskii (1979), who have shown that the dissolution rate of gold is controlled by diffusion (mass transfer) at agitation speeds below 100 rpm. However, in practice, the agitation speed is variable and generally lower than 100 rpm. It has been found that roasted gold ore (RGO) had the most positive potential (0.245 V), followed by hematite (0.235 V) and finally magnetite (Mag) (0.210) in 0.04 M NaCN solution after 2 h (at the end of test). These findings have indicated that corrosion potentials of electrodes have
less active potentials than pure gold electrode (-0.404 V) suggesting that these mineral electrodes can act as cathode in a gold galvanic coupling. Additionally, effect of slurry on the corrosion potentials of especially roasted gold ore (RGO) and pure gold (Au) disc electrodes, as well as rotating ring disc (RDE) and platinum (Pt) disc electrodes were tested for 24 h and the first 1 hour and the last 1 h (23-24h) were reported in Table 1.

In the first hour of test work, RGO (roasted gold ore electrode) reached to 0.170 V corrosion potential in the absence of slurry and 0.190 V in the presence of slurry. At the end of 24 h, RGO electrode had the close corrosion potential in presence and/or absence of slurry which suggests that oxidation products on the surface is more stable and resistant to dissolution. Moreover, according to first 1 h and the last 1 h in presence and/or absence of slurry, RGO electrode showed more tendencies to passive behaviour when compared to Au and rotating disc electrodes (RDE). This could be linked to the presence of different mineral phases and formation of surface products on the surface of RGO disc electrode.

Table 1 Corrosion potentials of different electrodes in absence and in presence of gold ore slurry in 0.04 M NaCN solution, pH 10.5 at 25 °C

<table>
<thead>
<tr>
<th>Type of electrode</th>
<th>Absence of slurry E/V</th>
<th>Presence of slurry (35%) E/V</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0h</td>
<td>1h</td>
</tr>
<tr>
<td>RGO</td>
<td>0.160</td>
<td>0.170</td>
</tr>
<tr>
<td>Au</td>
<td>-0.328</td>
<td>-0.404</td>
</tr>
<tr>
<td>RDE**</td>
<td>-0.436</td>
<td>-0.475</td>
</tr>
<tr>
<td>Pt</td>
<td>0.178</td>
<td>0.170</td>
</tr>
</tbody>
</table>

* The duplicate values of the same test of RDE for instance; **Rotating gold disc electrode (RDE) was removed from the solution and was kept under nitrogen atmosphere for 22 h just after the end of the initial 1 h to prevent surface corrosion.

In the absence of slurry, Au (pure gold electrode) reached to -0.404 V corrosion potential in the first hour. The same value was recorded after 24 h. Contrary, after 24 h in the presence of slurry, an inhibition in corrosion potential (-0.343 V) was found for Au electrode due to the presence of dissolved ions. This is probably due to the effect of oxide
products that were formed and accumulated on the surface of gold electrode. At the end of the experiment, it was also observed that the surface of gold electrode was covered with surface products and that can be attributed to the potential shift in the less active region.

In the absence of slurry (35%), in the first 1 h, corrosion potential of RDE was heading with a 40 mV potential change to more active region (-0.436 to -0.475V) and the same trend was also observed in the last hour (between 23 and 24 h). It is worth noting that RDE was removed from the solution and was kept under nitrogen atmosphere for 22 h to prevent corrosion (from the end of 1 h till the beginning of 23 h) and almost the same corrosion potential was obtained. As it is seen, there is somewhat difference (~ 70 mV) in the dissolution potentials of Au and RDE electrodes, where gold is present in both cases. This difference could be arisen since the surfaces of Au and RDE electrodes were subjected to different exposure times and preparation procedure which is mentioned in Section 2.3.1. Additionally, this could also be attributed to the efficiency of the two different agitation methods, and as a result the difference in quantity and the quality of surface products. However, in the first hour in presence of slurry, corrosion potential has been shifted about 20 mV (from -0.27 to -0.29 V) and 145 mV shift in active region (from -0.27 to -0.415 V) was observed for the last hour. This finding suggested that RDE undergoes more active behaviour. This could be attributed to the increase in the dissolution of gold.

In the absence of slurry, platinum (Pt) electrode had 0.142 V corrosion potential after 24 h while RGO electrode had 0.180V. This 35 mV difference suggested that more active behaviour for Pt surface compared to RGO. This could be attributed to the value of oxide-reduction reactions of cyanides on the noble platinum surface. Platinum electrode has also demonstrated more active behaviour in the absence of slurry after 24 h having the corrosion potential of 0.142 V compared to 0.170 V (in the first hour). In the presence of slurry, Pt electrode had almost similar corrosion potentials in the first hour and in the last 1 h, about 0.167 V that is almost the same as the initially obtained potential in absence of slurry. That means the slurry has no significant influence on the platinum
surface. This result suggests that platinum electrode can be suitably used as a counter electrode in gold and mineral disc polarization studies.

3.1.2 Electrochemical noise measurements (ENM) of Au and RGO electrodes

The corrosion potential and current noise were recorded for roasted gold ore disc electrode (RGO) and pure gold disc electrode (Au) in 0.04M NaCN solution during free corrosion. The anodic potential value of RGO constantly increased from 0.24 to 0.252 V while potential for Au showed a slight decrease and became stable at about -0.55 V. The current density variations in function of time showed a slight increasing trend from $4 \times 10^{-5}$ to $4.5 \times 10^{-5} \text{mA/cm}^2$ for RGO that suggested an increase in the dissolution of different minerals from RGO. However, current density for gold electrode was found to show almost the same trend through the test-work.

One of the important statistical parameters of ENM analyses in the time domain is the noise resistance ($R_n$). The noise resistance is defined as the ratio of the standard deviation of the potential noise to that of the current noise that can be associated to the polarization resistance ($R_p$). The ratio $1/R_n$ (admittance) is referred to the corrosion rate. The EN data values of $1/R_n$ for each specimen were measured during immersion period of 16 h. The mean of measurements for two series of mineral disc electrode and gold electrode were demonstrated in Fig. 2. ENM in-situ provides a general trend in corrosion rates of electrodes. In case of Au, it is subjected only to gold metal, whereas it is the dissolution behaviour of roasted gold ore for RGO electrode. However, the curve of RGO could be considered as the dissolution of gold, mainly. It is clearly seen that Au generally showed an increasing trend in the corrosion rate of gold until the end of test (24 h), while RGO showed a decreasing trend after initial 10 h. RGO and Au had the same corrosion rate of $1.29 \times 10^{-2} \text{ (mho/cm}^2\text{)}$ at 8 h. Then, the corrosion rate of RGO was found to be flat till the end of the test. This decrease in corrosion rate of RGO by the time could be linked to the presence of detrimental minerals mainly to gold dissolution. At the end of the test, two electrodes had very close corrosion rates. For active and passive regions of the surface, electrochemical noise measurement (ENM), as a novel tool, could be suitably used for corrosion tests of gold since ENM in-situ provides potential and current noise that gives
instantaneous corrosion rate (Eden, 2011). The main advantage of ENM is the in-situ measuring corrosion rate as function of time. On the other hand, using high agitation speeds in ENM could parasite the noise data and that may be considered as a negative point in application for gold leaching studies. It is also important to mention that although ENM technique was used for many different metals such as steel (Klapper et al., 2013), copper (Safizadeh and Ghali, 2013), zinc (Zhang et al., 2005), aluminium (Curioni et al., 2013) etc., there is a paucity of in-situ ENM studies on gold leaching.

![Instantaneous measured corrosion rate (1/R_n) for roasted gold ore and pure gold electrodes immersed in NaCN (0.04 M) solution by ENM after potentiodynamic polarization followed by potentiostatic test (2h) in absence of agitation, pH 10.5, 25 °C](image)

Fig. 2 Instantaneous measured corrosion rate ($1/R_n$) for roasted gold ore and pure gold electrodes immersed in NaCN (0.04 M) solution by ENM after potentiodynamic polarization followed by potentiostatic test (2h) in absence of agitation, pH 10.5, 25 °C

3.1.3 Scanning reference electrode technique (SRET) analysis of Au and RGO electrodes

It has been claimed that each point on the mineral surface (e.g. gold) 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 (Crundwell, 2013). This argument depends on the other closest constituents in an electrolyte. Habashi and Bas (2014) stated the existence of anodic and cathodic zones during the dissolution of minerals with certain experimental results.
The 3-D SRET images of potential differences measured over the surface of pure gold electrode (Au) and roasted gold ore disc electrode (RGO) as a function of immersion time (1, 8 and 16 h) in 0.04M NaCN solution are shown in Fig. 3. The active pits on the surface of each specimen can be observed. The potential differences were distributed into different zones corresponding to neutral, low and intense anodic and cathodic activities. The most anodic (most active) potential is the lowest point in the down cones and the most cathodic (less active) potential is the maximum point reached in the up cones. According to real time surface evolution of specimens, it is evident that the location of the pits at the surface changes with time. At the beginning of the test, the most active (anodic) potential of Au electrode was ~ -87 µV with respect to saturated calomel electrode (SCE) (Fig. 3a) and it was decreased to -20 µV/SCE (Fig. 3c) at the end of the experiment after 16 hours. It can be deduced that due to the decrease in most active potentials, less active (most cathodic) potentials on the surface of pure gold electrode were increased. This result suggests that the surface of the gold became passive by the time due to the formation of oxide and/or insoluble cyanide films (Kirk et al., 1978; Nicol, 1980). This was consistent with the potentiodynamic polarization results where pure gold showed a certain passive peak and the current density was sharply decreased to around zero. On the other hand, the most active (anodic) potential of RGO was around -20 µV during 16h. Most cathodic potentials for RGO were found to be higher (Fig. 3d) if compared to active (anodic) potentials at the on-set of the test (after 1 hour) but cathodic potential values decreased by 15 µV (Fig. 3f) with increasing the immersion time (after 16 hours). By the time passed, most active (anodic) and most cathodic (cathodic) potentials of RGO electrode showed a similar trend (Fig. 3e and f).

The potential difference between the most active anode and the dominating reactions on cathodic sites has the same trend as the electromotive force (EMF) of the most active corrosion cell and the real EMF should be proportional to the potential difference measured in-situ. Then, “quasi electromotive force” (QEMF) could be used to express the potential difference between the more probable anodic or cathodic reactions based on thermodynamic values on electrode surfaces in cyanide medium. Thus, initiation and propagation of pitting corrosion for the tested specimens can be then identified (Zhang et
The QEMF of corrosion cell as a function of immersion time for each specimen in 0.04M NaCN solution at pH 10.5 and 23°C was demonstrated in Fig. 4. The QEMF of Au suddenly decreased ~ 100 µV (from 150 to 45 µV) in the corrosion cell at the beginning of the immersion time and then became stable ~ 43 µV until the end of the test.

On the other hand, QEMF of RGO initially decreased by 17 µV and then was kept at 38 µV. Average QEMF values of Au and RGO were found to be 48.4 and 38 µµV, respectively. It is seen that RGO had lower QEMF if compared to Au, suggesting that RGO showed higher corrosion resistance whereas Au specimen was quickly attacked. Considering the QEMF of the different samples (Fig. 4) and measuring the depth of the pits of the two specimens, it can be deduced that the Au specimen had the deepest pits. It can be observed that after 8h up to 16h, similar trend in QEMF was observed for both

<table>
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<tr>
<th></th>
<th>Most active (anodic)</th>
<th>2nd stage anodic</th>
<th>1st stage anodic</th>
<th>Less cathodic</th>
<th>Most cathodic</th>
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<tr>
<td>Fig. 3</td>
<td>3-D SRET potential images at different immersion times in 0.04M NaCN solution at pH 10.5 and 25°C for (a) Au at 1h, (b) Au at 8 h, (c) Au at 16 h; (d) RGO at 1h, (e) RGO at 8 h and (f) RGO at 16 h</td>
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electrodes (Au and RGO). Since the presence of one phase in Au electrode, it gives rise to anodic and cathodic sites. RGO has many phases that could give rise to different electrochemical cell sites and even passive regions. However, almost same QEMF was obtained for both electrodes at the end of the test. After a 16 hours of exposure time, almost the same QEMF was observed for both of electrodes. SRET results showed that the QEMF is almost the same for anodic and cathodic reactions of pure gold and that of RGO. The cathodic and anodic reactions on gold are the dominating ones than that of silver due to its higher affinity and concentration in roasted gold ore. This result also confirms that the corrosion rate for RGO electrode (in Fig. 2) corresponds mainly to the dissolution behaviour of gold. The reproducibility of the QEMF values for Au and RGO electrodes were found to be ± 10% and 12%, respectively. These results have indicated that SRET in-situ corrosion measurements without any imposed potential, which is very close to practice, provide significant information on the corrosion behaviour of gold and show the existence and polarisation of anodic and cathodic sites during the leaching of gold.

Fig. 4 QEMF corrosion cell vs. immersion time in 0.04M NaCN solution at pH 10.5 and 25°C for pure gold (Au) and roasted gold ore (RGO) disc electrodes
3.2 Potentiodynamic polarization of Au, RGO, and oxide mineral electrodes

3.2.1 Cathodic polarization

Fig. 5 shows the cathodic polarization profiles of electrodes by scanning from $E_{corr}$ to $-300$ mV at pH 10.5 at 100 rpm agitation in 0.04 M NaCN electrolyte. In addition, cathodic polarization of pure gold was performed by scanning using the reverse direction (from $-300$ mV to $E_{corr}$, which was shown as Au* in Fig. 5) for comparison. As it is seen, there is an obvious difference in pure gold cathodic polarization curves. Oxygen reduction takes place in cathodic area (Eq. 6) with a 605 mV standard potential at pH 10.5. The standard potential of other possible reactions in cathodic section are given vs. standard hydrogen electrode in Eqs.7 and 8 (Aghamirian and Yen, 2005; Ahmed, 1978). The difference in conductivity and relative quantities of magnetite and hematite could explain the behaviour of RGO. Also, the presence of soluble and/or insoluble ions, and as a result different behaviours of these ions in the solution could influence the position of RGO electrode. Magnetite, hematite and gold ore at high over-potentials are less active than gold. At low over-potentials, hematite was more active than magnetite. This can suggest that magnetite and hematite are good electrocatalysts for oxygen reduction.

\[
\begin{align*}
\text{O}_2 + 2\text{H}_2\text{O} + 4e^- & \rightarrow 4\text{OH}^- & \quad 605 \text{ mV vs SHE} & \quad (\text{Eq. 6}) \\
\text{O}_2 + \text{H}_2\text{O} + 2e^- & \rightarrow \text{HO}_2^- + \text{OH}^- & \quad 55 \text{ mV vs SHE} & \quad (\text{Eq. 7}) \\
\text{HO}_2^- + \text{H}_2\text{O} + 2e^- & \rightarrow 3\text{OH}^- & \quad 1.14 \text{ V vs SHE} & \quad (\text{Eq. 8})
\end{align*}
\]
Fig. 5 Potentiodynamic cathodic polarization of different electrodes with scan rate of 0.166 mV/s in 0.04M NaCN electrolyte at 100 rpm agitation at atmospheric oxygen, pH 10.5, 25 °C (Au** indicates the cathodic polarization by scanning from -300 mV to E_{corr}).

3.2.2 Anodic polarization

It is seen that gold oxidation starts ~ -0.4 V/SHE (Fig. 6). Gold showed three passive peaks at around -0.1, 0.4, and 0.7 V with current densities of 0.2, 2.3, and 1.8 mA/cm², respectively. AuO{\text{OH}}_{\text{ads}}, AuCN_{\text{ads}}, [Au(III)OH(CN)₃]_{\text{ads}}, and Au(OH)₃ products are believed to be responsible for the formation of these passive peaks (Kirk et al., 1978). Furthermore, Bas et al. (2015) characterized gold surface by XPS after polarization tests and found Au¹⁺ and Au³⁺ corrosion products as responsible for the passivation of gold surface.
Fig. 6 Potentiodynamic anodic polarization of different electrodes with scan rate of 0.166 mV/s in 0.04M NaCN electrolyte at 100 rpm agitation, pH 10.5, 25 °C (Au: 1 cm$^2$; other electrodes 4.9 cm$^2$)

In case of RGO electrode, which was prepared using roasted gold ore sample, its current density increased slightly up to 0.75 mA/cm$^2$ till the end of the test. The different anodic behaviours of gold and roasted gold ore electrodes could be attributed to the mineralogical composition of gold ore. Potentiodynamic polarization studies in presence of strong agitation gives less information on peak identifications especially for non-pure metal systems. Detection of intermediate species in the double layer needs the presence of a certain quantity of the transient in close contact with the surface. Then, the presence of different soluble and/or insoluble species at the interface has certain influence on detection of different peaks and possess either positive or negative effect on the dissolution behaviour of gold. Dissolution of magnetite, which is a known iron oxide phase, started at more positive potentials if compared to gold. Magnetite (Fe$_3$O$_4$) is one of the most common Fe$^{3+}$-containing oxide minerals. Magnetite oxidation (Eq. 9) results in the generation of maghemite ($\gamma$-Fe$_2$O$_3$), metastable spinel polymorph of hematite (White et al., 1994). Hematite (Fe$_2$O$_3$), other most found iron oxide mineral, dissolution started earlier and it had higher current density if compared to magnetite. Conductivity of
magnetite (Fe₃O₄) is ~ 10⁶ times higher than that of hematite (Fe₂O₃), due to electron exchange between the Fe²⁺ and Fe³⁺ (Greenwood and Earnshaw, 1997).

\[ 2[Fe^{2+}Fe_2^{3+}]O_4(\text{magnetite}) + H_2O \leftrightarrow 3\gamma[Fe_2^{3+}]O_3(\text{maghemite}) + 2H^+ + 2e^- \]  \quad (Eq.9)

3.3 Effect of leaching parameters on anodic polarization of RGO electrode

3.3.1 Influence of NaCN concentration (0.01-0.04-0.1 M)

Various cyanide concentrations for a maximum gold leaching rate in practice have been reported by many research groups and the range of 0.004-0.05 M NaCN was generally accepted depending on the mineralogy, type of gold ore, and experimental conditions (Fleming, 1999). The influence of NaCN concentration on the polarization of RGO disc electrode at pH 10.5 at 100 rpm agitation is demonstrated in Fig. 7. It is seen that current density resulted in an increasing trend with increasing cyanide concentration. Oxidation started earlier at 0.04 M NaCN if compared to other ones. Polarization curves of 0.04 and 0.1 M intersected at 0.9 V having the same current density of 0.35mA/cm², then, higher current density was obtained at 0.1 M at the end of polarization test. Generally, it can be deduced that 0.04 M NaCN concentration gave higher current density in the potential range of gold dissolution (lower than 0.9 V/SHE). This behaviour in 0.04 and 0.1 M NaCN concentrations could be linked to the presence of soluble species as function of time in the solution. The lower current density obtained at lower cyanide concentration could be linked to the insufficiency of cyanide ions that would react with gold to dissolve. Current density of RGO was increased ~ 4 times with increasing NaCN concentration from 0.01 M to 0.1 M. These findings have revealed that oxidation of RGO commences earlier at higher cyanide concentration and 0.04 M seems to be more significant on dissolution process. On the other hand, it is generally believed that pure gold gives three peaks in cyanide solutions suggesting the passivation of gold surface (Kirk et al., 1980). However, Bas et al. (2015) has found that gold surface becomes relatively more passive and shows less than three passive peaks for lower cyanide concentration (<0.04 M) in tested values. Bas et al. (2015) has reported when gold is under passive conditions, increasing cyanide concentration, increasing pH, and potential have led to more passive behaviour, by using potentiostatic polarization.
Fig. 7 Effect of NaCN concentration on the polarization of RGO with scan rate of 0.166 mV/s at pH 10.5 at 100 rpm agitation, 25 °C

3.3.2 Influence of pH (10-10.5-11.5)

Hedley and Tabachnik (1968) pointed out the aim of adjusting/monitoring pH in cyanidation is to prevent the loss of cyanide by hydrolysis and by action of carbon dioxide in the air, to neutralize acidic compounds such as ferrous, ferric salts and to improve gold extraction when treating the ores containing tellurides (AuTe$_2$) which decompose more readily at higher alkalinites. Fig. 8 demonstrates the effect of pH on the polarization of RGO electrode in 0.04 M NaCN electrolyte at 100 rpm agitation. Anodic polarization profile was divided into two regions as A (till the potential of 0.9 V) and B (from the potential of 0.9 V to 1.2 V/SHE), since different trends have been observed. In region A, oxidation of roasted gold ore electrode started earlier at lower pH values (10-10.5) if compared to higher pH value of 11.5. Current density increased faster at lower pH values. The slow increasing rate of current density at high pH values (11.5) could be due to the presence of more hydroxides that promote the formation of passivating surface products (Habashi, 2009). However, in region B, a reverse trend was observed if compared to region A. Passing the potential of 0.9 V, current density reached to higher value at pH 11.5 than that of pH 10 and 10.5. This reverse trend in regions of A and B
could be linked to the presence of many different mineral phases in roasted gold ore and also difference in quantity of oxygen and free cyanide in the solution. Since gold leaching takes place in the region A (lower potential than 0.9 V), pH 10.5 seems to be more essential and effective value for the leaching of gold from RGO electrode. Furthermore, corrosion rate at pH 10.5 was found to give ~ 1.7 times higher than that of pH 11.5. Mahmoodi et al. (2010) reported that gold extraction was increased by ~ 2% with increasing pH from 9.5 to 10, and became stable in the range of pH 10-11 and finally decreased by increasing the pH from 11 to 12. Barsky et al. (1934) reported the decrease in gold dissolution above pH 11. Then, in this current study, pH 10.5 was selected as the optimum value. However, the optimum pH value for leaching should be selected depending on the type of gold ore, mineralogy and leaching system (Marsden and House, 2006). These obtained results in this tested conditions suggested that the range of pH 10-10.5 was found to be more preferable for gold leaching processes. Similarly, in recent gold galvanic studies depending on the type of gold ore and minerals, pH was maintained at 10.5 and 11 by Aghamirian and Yen (2005) and Azizi et al. (2010), respectively.

Fig. 8 Effect of pH on the anodic polarization of RGO electrode at 0.166 mV/s scan rate in 0.04 M NaCN electrolyte at the agitation of 100 rpm, 25 °C
In previous study (Bas et al., 2015), authors have found peak current densities of pure gold decreased with increasing pH values (10 to 12) at 100 rpm agitation in 0.04 M NaCN solution. The second peak current density was greatly increased (~ 40 times) at pH 10 if compared to other two pH values. At higher pH values (> 10), first peak current density was found to be very small (~ 0.05 mA/cm²). Additionally, low level of agitation (60 rpm) was tested at pH 11, since agitation is a significant parameter for the electrochemical dissolution of gold. It was found that decreasing agitation from 100 to 60 rpm has resulted in a great increase in the second peak current density which was very close for that of pH 10. The third peak at 60 rpm agitation gave almost the same current density if compared to the 100 rpm agitation.

3.3.3 Influence of agitation (100-250-400 rpm) on Au and RGO electrodes
Three passive peaks at -0.1, 0.3, and 0.7 V/SHE were observed as responsible for the passivation of pure gold surface (Fig. 9). Current density of second peak was found to be higher (~5 times) than that of the two other peaks. It was found that current density decreased by increasing agitation from 100 rpm to 400 rpm. In the case of pure gold and clean cyanide solution systems, effect of agitation on the anodic behaviour of gold was examined by some research groups (Kirk and Foulkes, 1980). Principally agitation does not promote the peak formation since the presence of intermediates at the interface becomes more limited. Second peak, known as a less anodic gold dissolution peak, could be passivated due to the oxygen adsorption (Dorin and Woods, 1991), gold oxide formation (Guan and Han, 1994), and by the formation of gold (I) hydroxide according to Au + OH⁻ → AuOHₐds + e⁻ (Kirk et al. 1978), or by the conversion of Au(I) to Au (III) was 2CN⁻ + [Au(I)OHCN⁻]ₐds → [Au(III)OH(CN₃)⁻]ₐds + 2e⁻ (Cathro and Koch, 1964). Moreover, the adsorption of cyanide ions was found to initiate the passivation of second peak (Poskus and Agafonovas, 1995).
Fig. 9. Effect of agitation (1: 100 rpm, 2: 250 and 3: 400 rpm) on the anodic polarization curve of pure gold (Au) electrode with scan rate of 0.166 mV/s in 0.04 M NaCN solution, pH 10.5, 25 °C

On the other hand, till now, examining the influence of agitation for electrochemical studies of gold ore systems (i.e. roasted gold ore) in cyanide solution was not much considered. Fig. 10 demonstrates the effect of magnetic agitation on the polarization of RGO in 0.04 M NaCN electrolyte at pH 10.5. It is seen that increasing agitation from 100 to 250 rpm, resulted in ~ 3 times (from 0.4 to 1.2 mA/cm²) higher current density at the end of polarization. However, increasing of agitation from 250 to 400 rpm showed around 15% lower current density. The decrease in current density above 250 rpm agitation speed could be explained by the increase in the mineral leaching from roasted gold ore electrode. As a result, higher agitation speeds could favour the release of more soluble and/or insoluble corrosion products that retards the further anodic behaviour of RGO. Also, it could lead to less time for the presence of certain reaction intermediates at the interface. Azizi et al. (2010) examined the influence of rotation speed for a gold and sulphide mineral electrode galvanic corrosion and found that the leaching was progressively decreased at rotation speeds above 400 rpm. It is also important to note that till now, the influence of agitation/rotation speed on mineral electrode leaching has received less attention and needs further detail examinations.
Kakovskii and Kholmanskikh (1960) found that dissolution of gold increases up to a certain agitation speed (150 rpm) then decreases or becomes flat. Cathro (1961) examined the effect of agitation on the corrosion rate of gold electrode and reported that increasing agitation has led to the decreasing gold corrosion rate. Similarly, Aghamirian and Yen (2005) reported that high electrode rotation speed reduced the maximum current density as a result of loss of hydrogen peroxide ions. These findings in these tested conditions have revealed that ~ 250 rpm agitation seems to be more effective for mineral electrode dissolution. Duplicate results are reproducible with a 6 % shift at different agitation levels on the anodic polarization of RGO. Then, it is important to underline that agitation provides important information about diffusion, mechanism and the rate of reaction.

Fig. 10 Effect of agitation (100, 250 and 400 rpm) on the anodic polarization curve of RGO with scan rate of 0.166 mV/s in 0.04 M NaCN solution, pH 10.5, 25 °C

3.4 Corrosion rate of Au, RGO, and combined disc electrodes

In linear polarization tests, potential and current values are plotted and the slope of this curve, denoted as the polarization resistance, $R_p$, and this value is used to calculate
the corrosion current ($i_{corr}$) utilising the well-known Stern-Geary equation (ASTM G102-89, 2006). Similarly, cathodic Tafel polarization can also be used to calculate corrosion current since anodic Tafel is not suitable due to the presence of passive behaviour in anodic polarization.

In this study, the effect of agitation speed (100, 250, 400 rpm) on the dissolution current (referring to dissolution rate) of pure gold (Au, 1cm$^2$) and roasted gold ore (RGO, 4.9 cm$^2$) electrodes alone and also combined together was examined by only cathodic Tafel polarization and the data obtained was presented in Table 2. It is seen that the dissolution current of Au electrode increased by ~ 2 times with increasing agitation speed from 100 to 250 rpm (7.69 to 14.28 µA). Then, it was decreased by 1.9 times to 7.21 µA at 400 rpm. On the other hand, the dissolution current of roasted gold ore (RGO) increased by 2.6 times (from 1.19 to 3.13 µA) with an increase in agitation speed from 100 to 250 rpm, and then showed a slight increase having of 3.69 µA at 400 rpm agitation (Fig. 11). In addition, corrosion current of electrodes were calculated manually and very close values were obtained to that calculated by using EC-Lab software. It can be deduced that increasing agitation speed gave an increase in the rate of dissolution for diffusion controlled systems till a maximum level where the rate remains constant. At this level, the contribution of diffusion is minimized and the rate of dissolution was controlled by chemical reactions in bulk phase or at interface. Furthermore, ~ 4 times lower corrosion current (for different metals) was observed for RGO electrode after 2 and/or 3 times using polishing, if compared to fresh RGO one (not shown). Due to the presence of many different mineral phases in RGO electrode, it has high sensitivity to dissolution. This result suggests the importance of polishing/preparation procedure and recommends also the use of new electrodes (fresh exposed surfaces) and that could be suggested in practice. It is important to note that results were reproducible.

On the other hand, corrosion current of electrodes were calculated from linear polarization by utilising the Stern-Geary method. Corrosion current of pure gold electrode was found to give close values by Stern-Geary method (6 ±4.13%, 14 ±3.64%, and 7.3 ±0.6%, at 100, 250 and 400 rpm, respectively). However, certain difference was
observed for roasted gold ore (RGO) electrode (4.9 ±4.88%, 6.1 ±3.08%, and 4.7 ±4.14% at 100, 250 and 400 rpm, respectively). Since the results obtained in the range of 100-400 rpm agitation speed is significant, then the wide range of agitation speed (0, 50, 600 rpm) was considered for RGO electrode by utilizing both methods. Corrosion currents of 0.162, 0.196, 0.045 µA by Stern-Geary and 0.077, 0.154, 0.071 µA by cathodic Tafel polarization were calculated at 0, 50, 600 rpm, respectively. It can be deduced that when the specimen is not pure, i.e. complex systems, a certain difference is appeared between Stern-Geary and cathodic Tafel slope methods when compared. Furthermore, to test the reproducibility and reliability of cathodic polarization, manual calculation of cathodic Tafel constant (βc) was used in the calculation of corrosion current by Stern-Geary method and very close values were obtained for pure gold electrode (7.69, 8.1 µA) and roasted gold ore electrode (1.19, 1.52 µA).

![Graph showing cathodic polarization curve](image)

Fig. 11 Effect of agitation (100, 250 and 400 rpm) on the cathodic polarization curve of RGO with scan rate of 0.166 mV/s in 0.04 M NaCN solution, pH 10.5, 25 °C
Table 2. Dissolution rate (calculated from cathodic Tafel polarization slope) of electrodes (pure gold (Au) electrode with a surface of 1 cm$^2$, roasted gold ore (RGO) electrode with a surface area of 4.9 cm$^2$) (*$^1$ is calculated by extrapolating Tafel slope to OCP for comparison)

<table>
<thead>
<tr>
<th>Electrode configuration</th>
<th>Dissolution current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 rpm</td>
</tr>
<tr>
<td>Au (1 cm$^2$)</td>
<td>7.69 ±1.64%</td>
</tr>
<tr>
<td></td>
<td>8.1 ±4.9%*$^1$</td>
</tr>
<tr>
<td>RGO (4.9 cm$^2$)</td>
<td>1.19 ±2.63%</td>
</tr>
<tr>
<td></td>
<td>1.52±3.30%*$^1$</td>
</tr>
<tr>
<td>Au connected to RGO</td>
<td>15.42 ±3.84%</td>
</tr>
</tbody>
</table>

Since cathodic Tafel and Stern-Geary methods gave different results, then it should be questioned which method is more suitable and reliable for the calculation of dissolution rate of gold from RGO. Since cathodic Tafel slope had a good region and provided reproducible results, then it could be proposed that this curve could correspond to gold mainly. Therefore, to support this idea, the corrosion rate of gold by cyanide leaching at 250 rpm agitation speed was compared to that obtained by cathodic Tafel slope. However, gold content from RGO in the solution in the absence of gold ore slurry after polarization was analysed and found to be lower than the detection limit. Therefore, conventional cyanidation tests of slurry in the absence and in the presence of RGO disc electrode were performed, and the difference in the measured values by AAS was considered as the leaching rate of Au from RGO disc electrode. It is important to note that gold had very close corrosion rates of $3.30 \times 10^{-8} \pm 3.27\%$ mol m$^{-2}$ s$^{-1}$ and $3.07 \times 10^{-8}$ $\pm 7.03\%$ mol m$^{-2}$ s$^{-1}$ obtained by cathodic Tafel slope and that obtained in conventional cyanidation, respectively. It can be noticed that corrosion current of Au (14.28 µA/cm$^2$) and RGO (0.64 µA/cm$^2$) (Table 2) shows ~ 30 times only in spite of the higher difference in gold content of the two specimens. This could be potentially linked to the electrolyte composition at the interface, passivation phenomena and electrochemical interactions.
Additionally, the intersection of cathodic and anodic curves was also considered for comparison, and the results were found to be deceptive and incomparable. These findings have confirmed that considering only cathodic Tafel slope scanning from $E_{\text{corr}}$ to more cathodic potentials in presence of cyanide ions and atmospheric oxygen provides representative results as in practical cyanidation, especially in presence of a good cathodic Tafel slope.

Kudryk and Kellogg (1954), one of the pioneer works in gold electrochemistry, have reported that the actual leaching rate (current) and potential of gold should correspond closely to the intersection point of the anodic (in absence of oxygen) and cathodic (in absence of cyanide) potential curves, separately. In this regard, Cerovic et al. (2005) considered the dissolution rate of gold from the intersection of cathodic and anodic curves. However, Dai and Breuer (2013) stated that considering only Evans’ diagrams did not reflect the leaching rate of gold since the mentioned conception of the electrolyte did not represent the practical conditions. These results and the findings in this work have created a new question to be examined why considering both (anodic and cathodic) Tafel curves, and Stern-Geary method did not give reliable results and not suitable for the estimation of dissolution rate of gold. The first reason could be linked to the presence of passive behaviour in anodic Tafel slope. Similarly, Stern-Geary method also considers both anodic and cathodic curves. Also, it can be speculated that soluble species (i.e silver, iron) could be dominating in the construction of linear polarization curves of Stern-Geary method. These findings have revealed that considering Tafel slopes and Evans diagrams for both (anodic and cathodic) curves for dissolution rate of gold or roasted gold ore electrodes are misleading and not comparable to that in practical cyanidation results. This conclusion is consistent with the recent findings of Dai and Breuer (2013) which says that leaching of gold starts earlier than the predicted one by Evans’ diagrams. It can be deduced that the consideration of the cathodic Tafel slope only is recommended since the corrosion rate especially in roasted gold ore is potentially controlled by the available active surface sites of gold. Then, extrapolation of the cathodic Tafel slope to OCP is the recommended technique.
It is believed that gold dissolution may be affected either in a positive or negative way when it is connected/associated with other minerals/metals (van Deventer and Lorenzen, 1987). When RGO (4.9 cm$^2$ surface area) was electrically connected to Au (1 cm$^2$ surface area), corrosion current of metals was increased by 15% (from 13.91 to 16.081 µA) at 250 rpm agitation if compared to 100 rpm and decreased by 22% to 13.10 at 400 rpm. This result is consistent with the findings for RGO electrode alone. This suggests that gold electrode promoted the gold dissolution possibly from both when electrically connected to mineral disc electrode due to the galvanic interaction. In general, two electrically connected electrodes indicated higher corrosion current due to the increase in surface area and electrochemical interactions. Additionally, in these tests, the effect of slurry on electrically connected electrodes was also tested. Although corrosion currents of gold and other metals were increased ~ 3 times when RGO was connected to Au, ~30% decrease in corrosion current (10.3 µA) was obtained when they were connected in presence of slurry. Then, it would be critical to use the leaching residue as a new feed material on the dissolution of Au electrically connected to RGO. After the polarization test, solid/liquid separation was done and the residue as solid was collected on the filter paper and then was put into the oven at least 6 h at 105°C. After drying process in oven, it was prepared to use as a new feed sample, slurry. This finding can be linked to the removal of soluble detrimental ions (e.g. iron species) in the first stage. However, if the tailings of the first slurry was used again as a new feed sample, corrosion current of RGO connected to Au electrode was increased by 1.6 times (16.2 µA). This increase could be explained by the removal of detrimental ions in the first stage and carrying the tailings to the subsequent cyanide leaching and dissolved ions have significant effect on the leaching kinetics.

A brownish-red color (Fig. 12a) was observed on the surface of Au electrode after the test. This was analysed by scanning electron microscopy (SEM) indicating the presence of iron-oxide species (Fig. 12b) released from RGO electrode that passivates Au surface. These findings have revealed that released species from mineral electrodes are responsible for the passivation of gold as a retarding effect on gold leaching.
Fig. 12 (a) Surface image of Au electrode after combined with RGO electrode test showing the brownish-red color; (b) SEM image of Au electrode surface

4 Conclusions

The conclusions of this study are summarized as below:

1. In open circuit potential (OCP) tests, roasted gold ore (RGO) electrode showed less active behaviour than that of gold (Au) electrodes. In electrochemical noise measurement (ENM) tests, the corrosion rate of RGO electrode was found to show a plateau after initial 10 h till the end of the test (24 h) while Au electrode showed an increasing trend of corrosion rate. The difference in corrosion potentials of Au and RGO electrodes in OCP and ENM studies is highly dependent on agitation, oxygen, and different experimental conditions.

2. Employing SRET in-situ results at open circuit potential, as close to practice, Au electrode showed higher quasi electromotive force (QEMF) (150 vs. 50 µV/SCE) than that of roasted gold ore (RGO) electrode.

3. Potentiodynamic polarization tests showed that:
3.1. Optimum conditions for the leaching of RGO electrode were found to be 0.04 M NaCN concentration, pH 10-10.5, and 250 rpm agitation. The dissolution rate of RGO electrode, pure gold, and also electrically connected electrodes increased up to maximum at 250 rpm then showed a certain decrease. It can be deduced that dissolved ions should have significant and different synergetic effects on gold leaching that could impact conductivity, and cyanide concentration of the solution.
3.2. In the presence of slurry, lower corrosion rate (current density) was obtained for electrically connected electrodes very possibly due to the presence of surface products that was observed by SEM analysis, leading to the passivation of gold surface. However, a 3 times higher corrosion rate was obtained if the tailing of the first polarization was used again as a new feed sample. Corrosion current of different metals for RGO and Au combination was increased by ~ 2 times, while it was decreased by ~ 30% in the presence of slurry. However, it was increased 1.6-fold if the tailing was used again as a new feed.

3.3. Cathodic (Tafel slope) potentiodynamic polarization curve of gold and roasted gold ore electrodes in presence of atmospheric oxygen and cyanide ions represents the practical leaching kinetics. The reliability of this approach was confirmed by the results obtained via conventional cyanidation.

3.4. Anodic and cathodic Tafel slopes (considering intersection point) and Stern-Geary methods in presence of cyanide and atmospheric oxygen could be misleading to estimate the leaching rate of gold and roasted gold ore potentially due to the passive behaviour in anodic curve.

3.5. Cathodic polarization scanning from $E_{\text{corr}}$ to more cathodic potentials provides more representative Tafel slopes and accurate results whilst scanning in the reverse direction is not suitable for gold leaching estimation.

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References


**Highlights**

- Electrochemical dissolution of roasted gold ore (RGO) was investigated.
- 0.04 M NaCN, pH 10-10.5, and 250 rpm agitation were found to be optimal for RGO.
- Consideration of cathodic Tafel and OCP for RGO represent conventional cyanidation.
- Anodic curve is misleading for corrosion rate estimation due to passivation.
- Fe-oxide species, responsible for partial passivation of gold, were observed by SEM.