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Biohydrometallurgy in Turkish gold mining: First shake flask and bioreactor studies

H. Ciftci, A. Akcil *

Department of Mining Engineering, Mineral Processing Division (Mineral-Metal Recovery and Recycling Research Group), Suleyman Demirel University, TR32260 Isparta, Turkey

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ABSTRACT

The first laboratory tests on biooxidation and cyanidation of gold ores in Turkey were carried out using samples of the Copler Gold Mine. Over a 3 year R&D test period, mixed bacterial/archaeal cultures improved biooxidation of the Copler ore. The highest sulphide oxidation of 87.35% over 432 h was achieved in shake flasks in the presence of the mixed culture (MODM: *Sulfolobus acidophilus* and *Sulfolobus thermosulfidooxidans*). Bioreactor tests resulted in greater dissolution rates for iron and arsenic than did shake-flask tests, which led to a greater extent of sulphide oxidation within a shorter period of time. The maximum sulphide oxidation in the bioreactor tests was 97.79% after 240 h when the EXTM (*Acidianus brierleyi* and *Sulfolobus metallicus*) mixed culture was used. After the biooxidation experiments with solids contents of 10% and 20% (w/v), the gold recovery from the oxidised ore was lower than that achieved in the presence of 5% solids (w/v) because the extent of sulphide oxidation was reduced as the pulp density increased. A strong correlation between the sulphide oxidation and gold recovery was also established. The highest gold recovery of 94.48% was achieved during cyanidation from the biooxidised ore produced from the experiment conducted using the EXTM mixed culture.

1. Introduction

Submicroscopic gold, which is typically trapped in a matrix of arsenopyrite/pyrite, cannot be effectively recovered, even when extensive fine-grinding processes are applied. To reduce the initial investment cost necessary for the construction a large-scale facility, the ore is typically crushed and milled, and a flotation concentrate is produced because gold is mostly found in the arsenopyrite/pyrite fraction. A pre-treatment process must be applied to the flotation concentrate before cyanide leaching. For the pre-treatment process, the flotation concentrate can be heated at 600–700 °C or treated with an acidic or basic solution under high pressure and temperature using an autoclave. Instead of using these methods, which are expensive or, in the case of heating, causes environmental problems, a biooxidation pre-treatment process was used (Komnitsas and Pooley, 1989). The biooxidation pre-treatment process is used to break up the crystal structures of minerals that contain gold. Thus, the contact area between cyanide and gold is increased, and the gold is more efficiently dissolved. This process can be performed under atmospheric pressure and at low temperatures, especially for low-tonnage production; furthermore, this process is more economical and compatible with environmental legislation. The use of microorganisms in the preliminary preparation processes of gold recovery from refractory gold ores began in the 1980s (Rawlings, 1998).

Although the biological processes used in the recovery of metals have been well known for centuries, the term "biohydrometallurgy" first appeared in 1972 in a manuscript titled "biohydrometallurgy of cobalt and nickel" (Torma, 1972). Biohydrometallurgy encompasses bioleaching, biooxidation, mineral biotechnology and biomining. The dissolution of sulphidic metals by biological processes is more environmentally friendly than other conventional chemical processes (Brierley and Brierley, 2001; Akcil, 2004; Ehrlich, 2004). The mesophilic iron- and sulphur-oxidising bacteria are widely used in the bioleaching/biooxidation process for the oxidation of sulphidic ores and flotation concentrates. Depending on the mineral, chemical attack occurs through a combination of ferric iron and acid (protons), whereas the role of the microorganisms is to generate the ferric iron and the acid. This strategy for metal recovery is known as bioleaching because the metal is solubilised in the process (Rawlings et al., 2003). Convincing evidence showing that microbes were active participants in the leaching of copper and some other metals from ores was not obtained until the middle of the twentieth century. This discovery led to a concerted effort to identify these microorganisms and their mode of action (Ehrlich, 2004).

Recently, metal recovery using biological processes (bioleaching and biooxidation) is more economical and compatible with wastes from production processes and low-grade ores than other methods, and interest in metal recovery through the use of biological processes is increasing (Brierley, 2010). The microorganisms used in these processes take on the role of a catalyst task in the leaching of ore. For this reason, the leaching process in the presence of

* Corresponding author. Tel.: +90 246 211 1321; fax: +90 246 2370859.
E-mail address: ataakcil@sdu.edu.tr (A. Akcil).

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bacteria occurs more rapidly under atmospheric pressure and at lower temperatures than do chemical processes. The most popular application of this process is the biooxidation of refractory gold sulphide ore. In this process, microorganisms are used to recover gold by oxidising and opening the crystal structure of gold sulphide minerals, such as arsenopyrite or pyrite. After the biooxidation pre-treatment process, the gold is dissolved in cyanide leach and recovered from this solution using zinc cementation or carbon adsorption procedure (Olson et al., 2006; Syed, 2012).

Several gold biooxidation plants were commissioned over the last 25 years and are progressing fast with rapid industrialisation. The first biooxidation plant was commissioned in 1986 by Gencor, at the Fairview mine in South Africa. The BIOX® process developed by Gencor, operates at 40–45 °C and is used by most stirred tank operations (Rawlings et al., 2003). In contrast, plants utilising BacTech technology operate at moderately thermophilic temperatures between 45 and 55 °C. Several more plants have been built, including a biooxidation plant at Sansu, Ghana. Commissioned in 1994, and expanded since, the plant processes 1000 tonnes of gold concentrate per day, and earns nearly half of the country's foreign exchange (Rawlings, 2002). Canadian-based BacTech mining company's bacox process is used for the treatment of refractory gold concentrates. Three plants using the process are in operation, with the most recent plant at Liazhou, in the Shandong province of China, owned by Tarzan Gold Co. Ltd. Recently the BacTech Company has signed an agreement on June 2008, to acquire Yamana Gold in two refractory gold deposits in Papua New Guinea (Gahan et al., 2012).

In this study, laboratory biooxidation experiments were performed using mixed culture of mesophilic (MESM1), moderately thermophilic (MODM) and extremely thermophilic (EXTM) microorganisms on refractory gold ore from the Copler (CROM) mine prior to cyanidation. To increase the gold recovery efficiency of the direct cyanide leaching procedure, from which low gold recovery is typically obtained, the biooxidation process was performed in Erlenmeyer flasks or in a bioreactor before the cyanide leaching procedure. The oxidation ability and the performance of bacterial/archaeal cultures used in the biooxidation process of a refractory gold ore were investigated at different temperatures. Additionally, the oxidation rate of sulphide compounds was quantified to determine the influence on the gold recovery efficiency and on the cyanide consumption in the cyanidation step.

2. Turkish gold mining

Turkey has a large and diverse mineral resource base, and metal mining dates back at least 9000 years. Metals, including copper, gold, iron, lead, mercury, silver and tin, have been mined since ancient times by the Phoenicians, Greeks, Hittites, Romans, Ottomans and the modern-day Turkish people. Mineral deposits are numerous, but most are of modest size. The country is thought to contain almost 3% of the world's industrial mineral resources, including 60% of the world's borax, 20% of the world's bentonite and more than 50% of the world's perlite. The main products in the minerals sector include natural borates and concentrates, natural stone, ferrochromium, chromium ores, copper ores, magnesite, zinc ores, feldspar, pumice stone, kaolin and other clays. More than 50 different minerals are currently produced. However, considerable effort is now being devoted to the exploration for and extraction of gold (Ariana, 2010).

In Turkey, the estimated total number of gold ore beds is 267; 13 of these beds have a potential of more than 150 metric tonnes, 40 have a potential between 30 and 150 metric tonnes and 234 have a potential of less than 30 metric tonnes. Two gold mine beds were founded in Usak, which has a potential of approximately 208 metric tonnes, and in Erzincan, which has a potential of approximately 112 metric tonnes; these results confirmed those of the model study (Alkin et al., 2003). The country's first gold mine, Ovacik, opened in 2001, and the largest gold mine in Europe, Kisladag, opened in 2006. Other new mines include those at Kucukdere, Mastra, Copler, Efemcukuru and Kaymaz. Annual gold production in the country has now reached more than 0.5 Moz, and continues to increase (Ariana, 2010).

Gold was traditionally produced in Turkey as a by-product from the Çayeli mine, now owned by Inmet Mining Corp, from Turkish-owned (mainly state) operations on other base-metal deposits, and from the Gümüskoy silver mine, owned by Eti Gümüs AS. Gold production from the first true Turkish gold mine began in 1997 at the Ovacik mine then run by Normandy Mining; this activity, however, was short-lived. Following what became an infamous legal case and after four years of proceedings in and out of court, Ovacik eventually started commercial production in 2001. From only a handful of companies in 1990, approximately 30 gold exploration and mining companies currently operate in Turkey, at least two thirds of which were established by foreign investment. This enhanced exploration activity has increased Turkish gold resources/reserves from 16 tonnes in the early 1990s to 710 t by 2009. The fact that the potential resource inventory of Turkey could be as much as 6500 tonnes based on geological modelling indicates that the industry is still only in its infancy. In Turkey, new gold mines have begun operations in the past decade, and the country has become the largest European producer of gold, even eclipsing the combined production of previous leaders Sweden and Bulgaria. The commodity is also becoming increasingly recognised within Turkey as a significant direct and indirect contributor to the economy. As a result, local interest in the exploration for Turkish gold resources is at an all-time high (Sener, 2010).

3. Materials and methods

3.1. Gold ore sample

Refractory gold sulphide ore (Copler) was used in experimental studies. The ore sample was collected from Copler Village at the Cukurdere (Erzincan) gold mine bed of Anagold Mining Industry and Trade, which is a partnership company associated with Alacer Gold Corp. and Lidya Mining Industry and Trade.

The structure of the gold ore bed of Copler Village is complex, and the bed contains different types of copper–gold mineralisation. Mainly porphyry, marble, and Mn-containing zones are found in the gold mine bed according to feasibility studies performed by Rio Tinto, Inc. After drilling work was performed, the main porphyry zone contained 2.3 g/t Au with a total mass of 23 million metric tonnes, the marble zone contained 7.7 g/t Au with a total mass of 4 million metric tonnes, and the Mn containing zone contained 4.1 g/t Au with a total mass of 7 million metric tonnes (Kociumbas and MacFarlane, 2002). According to a report prepared by Anatolia Minerals Development Limited (2005), the ore bed contains 2.96 g/t Au, with a total mass of 11.6 million metric tonnes that can be recovered by milling and cyanide leaching processes, and 0.7 g/t Au with a total mass of 30.9 million metric tonnes that can be recovered by a heap leaching process. The sulphide ore reserve contains 0.7 g/t Au, with a total mass of 28 million metric tonnes. The ore bed may also contain 3 g/t Au, with a total mass of 15.5 million metric tonnes (Anatolia Minerals Development Limited (2005)).

Mineralogical and metallurgical pre-studies (cyanidation) and analyses of the ore bed were performed by Rio Tinto, Inc. Based on the feasibility studies, gold was not found to be suitable for