



Direct smelting of gold concentrates, a safer alternative to mercury amalgamation in small-scale gold mining operations

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Abstract: Mercury is used in small-scale mining to amalgamate gold particles, facilitating their separation from heavy sands. This method of extraction finds application in over 50 developing countries. However, due to careless handling, mercury may be lost to the environment mainly through inefficient amalgam distillation techniques and spillage. The negative environmental/health-related effects of mercury in mining communities in many countries have necessitated research interest into development of safer alternatives. This paper reports on a study regarding a safer alternative method of gold recovery; direct smelting. This process generates a final product in one-step as compared to the three-step amalgamation, retorting/heating and smelting, currently practiced. Direct smelting has the potential to replace amalgamation and retorting because it is more effective, easier, quicker and cheaper.

Key words: Gold, small-scale mining, mercury, direct smelting

I. Introduction

Mercury is used in small-scale mining to amalgamate gold particles, facilitating their separation from heavy sands. It may be added during comminution or after gravity concentration, when the gold is concentrated along sands with a characteristic black colour generally known as black sands. Amalgamation involves addition of mercury to the gold concentrate and vigorous mixing to induce mercury and gold particles to make contact, which results in a whitish amalgam. This is subsequently separated from the black sands, and after pressing out excess mercury, the amalgam is often heated in the open air to obtain a sponge gold.

This method of extraction finds application in over 50 developing countries (Appleton et al., 1999; Drasch et al., 2001; Babut et al., 2003; Serfor-Armah et al., 2004; Viega et al, 2006; Hilson et al., 2007; Tschakert and Singha, 2007). However, due to careless handling, mercury may be lost to the environment mainly through disposal of amalgam residues, inefficient amalgam distillation techniques and spillage. It is estimated that about 1000 tonnes of mercury is released into the general environment per annum. About 200–250 tonnes of mercury are released in China, and 100–150 tonnes in Indonesia. Other countries including Bolivia, Brazil, Colombia, Peru, Philippines, Venezuela, Ghana and Zimbabwe release up to 30 tonnes (Viega, 2006). According to the United Nations Industrial Development Organisation (UNIDO) there are about 30 million miners involved in this industry worldwide and virtually all of them utilize mercury in gold recovery (Anon, 2009a). The negative environmental/health-related effects of mercury in mining communities in many countries have necessitated research interest into development of safer alternatives.

Some safer methods that have been prescribed include winnowing, the coal gold agglomeration process, smelting, and leaching processes such as IGoli, Haber and cyanidation (Hilson and Monhemius, 2006; Amankwah et al, 2009). In coal agglomeration the final float concentrate has to be processed and smelted. On the other hand, IGoli, Haber and cyanidation processes utilise leaching reagents to dissolve gold, and solutions have to be processed further for gold recovery. By smelting the concentrates directly, a process could be developed that generates a final product in one step. Smelting is a technique that is already known to the miners, as they smelt sponge gold after amalgamation and retorting/heating. The one-step smelting technique was tested both under laboratory conditions and in the field, under the Ghana Mercury Abatement Project sponsored by the European Union.

II. The amalgamation/heating/smelting process

Amalgamation is a process where gold particles are incorporated into mercury to effect separation from associated sands. The process of amalgamation normally begins after gravity concentration, though in some cases mercury may be added during gravity concentration. Mercury is added to the gold concentrate and agitated

mechanically to effect contact with gold particles. The amalgam is then recovered as illustrated in Figure 1. The use of mercury is simple as it collects most of the gold particles and glues them together as shown in Figure 2. After heating the amalgam, mercury is vapourised, and the gold produced has a network of pores, which is referred to as sponge gold. The sponge gold is then smelted to obtain the gold bullion or what small-scale miners refer to as 'refined gold'. Unfortunately, these small-scale miners don't use personal protective wear in their operations (Figure 1), and this is a source of concern. The use of bear hands in handling mercury could introduce mercury into the operator's body as the skin can absorb through sweat pores. Mercury can also enter the body by inhalation, ingestion and injection.

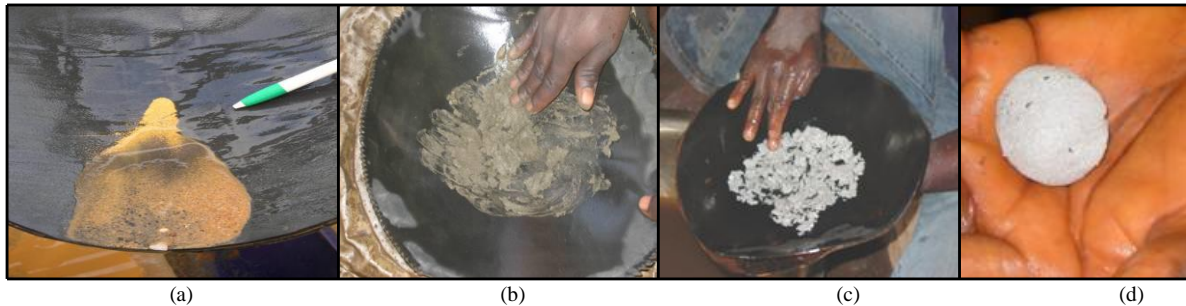


Figure 1. The amalgamation process showing (a) the clean gold concentrate (b) vigorous mixing after addition of mercury (c) separation of amalgam from sands (d) ball of amalgam

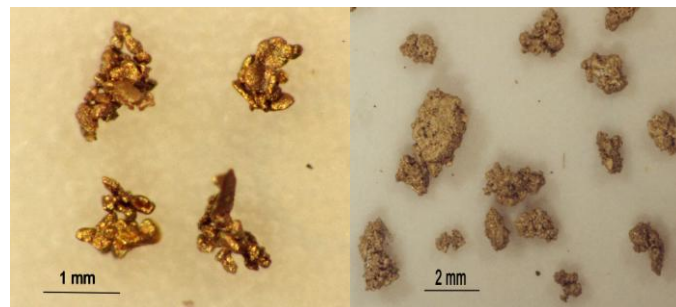


Figure 2. Gold particles glued together by mercury (Styles et al, 2006)

The impact of mercury on the public health of small-scale mining communities has been reported by several investigators (Appleton et al., 1999; Drasch et al., 2001; Babut et al., 2003; Serfor-Armah et al., 2004; Hilson et al., 2007; Tschakert and Singha, 2007). In a study at an Artisanal and Small-scale Mining (ASM) community in Ghana (Babut et al., 2001; 2003), it was reported that 20% of sampled persons had tremors and 65% had sleep disorders. Examination of mercury in biological samples indicated that between 86% and 91% of people tested had varying levels of mercury intoxication, and that the metal is having an impact on the public health of the community.

Due to these problems, retorts have been introduced to improve on the efficiency of amalgam distillation and diminish the escape of mercury fumes. Two major retorts available for use in small-scale operations around the world are the steel and Thermex glass retorts (Babut, 2001). Unfortunately, the miners do not patronize the Thermex glass retort due to its fragile nature and long heating times, especially for large pieces of amalgam. The steel retort is also not accepted due to its opaque nature which prevents miners from observing the process directly and darkening of gold after retorting.

III. The Direct Smelting Technique

The direct smelting technique was developed as a method with the potential to replace amalgamation and heating (Amankwah et al, 2009). This method begins with the gold concentrate that is prepared for amalgamation as presented in Figure 1a. The technique has been tried on concentrates obtained from all the main types of gold ores, namely refractory sulphidic gold ores, free milling and alluvial material. Refractory sulphidic concentrates, however, require pretreatment due to the mineralogy. Depending on the source of the material concentrated and the type of comminution process conducted, the concentrate may contain abraded steel components that have to be removed by a pretreatment stage.

A. Pretreatment of concentrates

A.1 Oxidation of sulphides

Sulphide concentrates have to be oxidized before or during the smelting process. Though the addition of potassium nitrate during smelting may lead to oxidation, it was realised in the study that the addition leads to

excessive boiling, with the potential for molten material to spill over from the crucible. Thus pre-smelting oxidation of sulphides is more acceptable.

During oxidation of sulphides, the concentrate is spread in a roasting pan and heated over an open fire for a period of up to 20 minutes while stirring. Microscopic investigation has shown that with ample supply of air, 20 minutes of roasting is enough to convert most of the pyrites to hematite. The sequence of oxidation observed is presented in Figure 3. In the cause of oxidation, some oxides of sulphur are released. The furnace developed is equipped with an extractor that directs the gases into a lime bath where they are neutralised.



Figure 3. Photomicrographs showing the conversion of pyrite to hematite during roasting (a) pyrite particle in the concentrate (b) partially oxidized pyrite with a boundary of hematite (reddish) after 5 min roasting (c) pyrite in an advanced stage of conversion to hematite after roasting for 10 min (d) hematite produced after 20 min

A.2 Removal of abraded steel

Some gold ores are very hard and thus, generally abrade and break sections of the mild steel grinding surfaces of the comminution equipment utilised. Since steel is heavy, the particles introduced into the ore eventually end up in the concentrate. Steel is magnetic and therefore magnetic separation is a method of choice for removing the pieces.

The concentrate is pulped and the magnet, enclosed in a transparent polythene bag, is then brought into contact with the pulp. The magnetic material is picked up and later washed into another bowl after demagnetization. This is done several times until all the magnetic materials have been removed. Due to the ferromagnetic properties of the abraded steel, it is necessary to use a very low intensity magnet (as low as 5.0×10^{-3} Tesla) to prevent trapping of free gold particles between steel pieces. Magnets of the strength similar to that of the magnetic alphabet set (that are usually stuck on fridges) were found to be suitable.

B. Smelting furnaces

Two furnaces have been constructed for the field application of this process; a gas and a charcoal fired furnace. The furnaces have been christened *sika bukyia* by small-scale miners in Ghana. The charcoal-fired furnace has a steel shell and a heating chamber lined with refractory bricks as shown in Figure 4. The external dimensions of the furnace are 50 cm x 35 cm, and the combustion chamber has dimensions 35 cm x 20 cm. It can accommodate two smelting crucibles at a time. The unit stands at a height of about 80 cm, and a removable hood of height 120 cm is equipped with an exhaust fan which propels gases out of the combustion chamber and away from the operator.

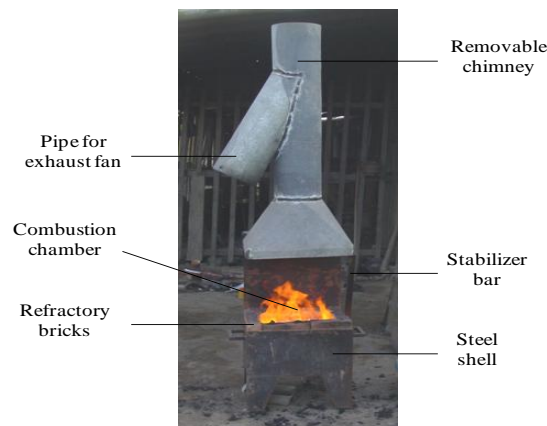


Figure 4. The charcoal fired furnace (Amankwah et al, 2009)

The use of charcoal, although regarded as both cheap and easily available to small-scale miners, has environmental implications, and so, a gas-fired furnace was developed to ameliorate this. The gas-fired furnace

shown in Figure 5 stands at a height of 30 cm, has an internal diameter of 16 cm and is equipped with an air inlet valve and a hood. It is capable of taking one crucible at a time. A cylindrical cross section was chosen with the fuel inlet tangential to the cylinder. This was to allow the flame to circulate in the chamber for uniform distribution of heat. Slots/grooves were cut on the fuel injection pipe to aid oxygen injection. Ceramic fibre was used for insulation.

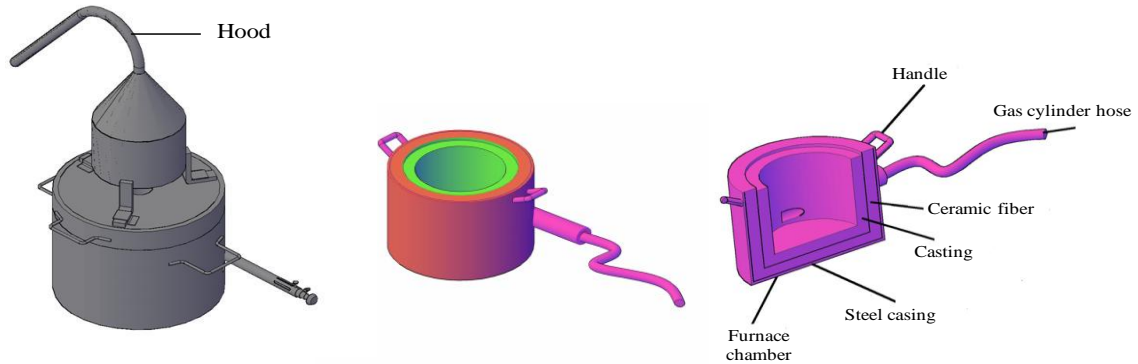


Figure 5. Pictorial illustration of the gas-fired furnace

C. Fuels utilised for the smelting operation

Gold melts at 1063°C , thus a furnace for smelting gold concentrates should be able to maintain a temperature above this value. The temperature profile achieved by each of these fuels is presented in Figure 6. The profile of LPG shows that, there was a rapid rise in the temperature of the combustion chamber from room temperature to about 300°C within the initial 3 min. The temperature increased further to about 1300°C after 10 min. the temperature attained after 30 min was 1600°C . The profile for charcoal shows a slow initial rise in temperature reaching about 50°C in the initial 3 min. There was a sudden rise to above 1200°C after 10 min, beyond which the profile approached a plateau.

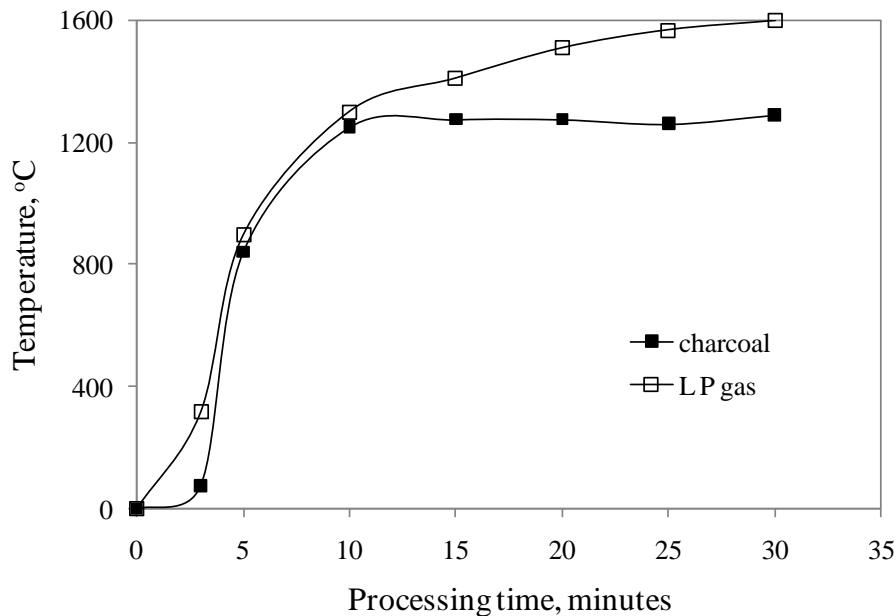


Figure 6. Temperature profile for L P gas and charcoal

It was observed that about 0.7 kg of LPG was used for a full direct smelting cycle, while between 10 kg and 12 kg, in the case of charcoal. This is due to the higher calorific value of LPG over that of charcoal (Anon, 2009b). In a related study, palm kernel shells were used as fuel in place of charcoal. Though the temperature attained was high enough for smelting gold, the bed on which to mount the crucibles was not stable and the flames generated were high and difficult to control (Amankwah *et al.*, 2009).

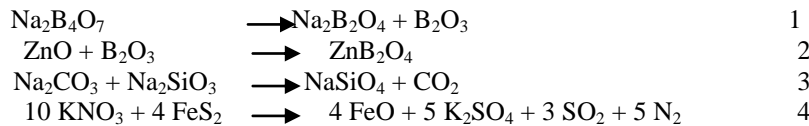
D. Fluxing and smelting

Smelting is basically a melting process, and the charge for smelting is heated till it becomes molten. In preparing material for smelting, some components known as fluxes are added in order to reduce the melting

temperature. On melting, the flux serves as a collector of the impurities. In addition, the flux protects the furnace liners or crucibles from direct attack of the molten material and inhibits volatilization.

The common fluxes used in smelting gold concentrates include sodium tetraborate or borax ($\text{Na}_2\text{B}_4\text{O}_7$), silica sand (SiO_2), and potassium nitrate (nitre, KNO_3). Silica melts at very high temperatures, and is able to dissolve most of the base metal oxides to form a viscous slag. Borax is added to reduce the melting point of the charge and the viscosity of the resulting slag. Nitre is an oxidizing agent, and oxidizes many base metals and metal sulphides present so that they can be slagged. Sodium carbonate reduces slag viscosity and improves slag clarity. The major reactions of borax, soda ash and nitre are represented by Equations 1 to 4. Silica is a flux but it may not be added directly in this process, as the gold concentrates generally retain enough silica for the process.

Borax melts to form a colourless transparent glass, consisting of a mixture of sodium metaborate and boric anhydride (Equation 1). The boric anhydride then reacts with the metal oxide (e.g. zinc oxide) to form the metal borate (Equation 2).



The percentage of each chemical in the smelting charge depends on the type of concentrate to be smelted. Free-milling concentrates and alluvials use the same composition. For refractory sulphidic concentrates, there is the need to pretreat by roasting. After the pretreatment process, it responds just like the initial two types of concentrates. Both laboratory investigations and fields trials indicate that one part of the concentrate can be mixed with two parts of borax and two parts of soda ash for a good smelting operation (Figure 7).

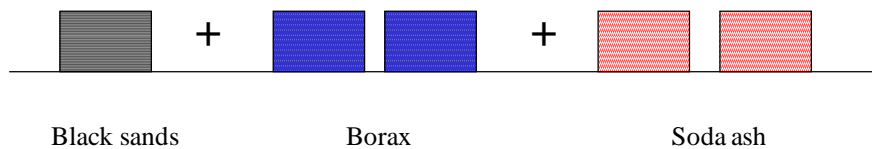


Figure 7. The combination of gold concentrates (black sands) and fluxes for the direct smelting process

After mixing, the charge is poured into crucibles and placed in the already lit furnace. The smelting process using either of the fuels can be completed within 30 mins. On removing the crucible with tongs, the molten material is poured into moulds and allowed to cool before gold is separated from the slag (Figure 8). The crucibles used could take a maximum of 60 g of gold concentrate, and the minimum weight of gold recovered by this method was 0.2 g.

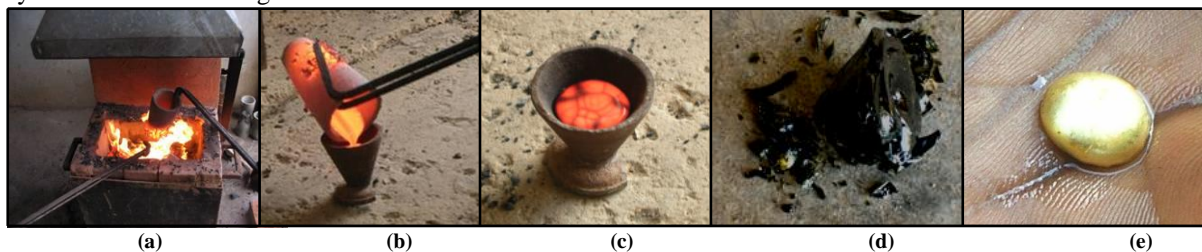


Figure 8. The direct smelting process (a) removing crucibles from the furnace (b) pouring of molten charge (c) molten material cooling down (d) separation of slag from gold (e) smelted gold

Direct smelting has the advantage of recovering occluded/coated gold particles that report in the concentrate that cannot be picked up by mercury. Sulphides in the concentrate will decompose and release the contained gold, and very fine particles that escape during squeezing of excess mercury from the amalgam will be also retrieved.

It was realised from both the laboratory study and field trials that direct smelting is a viable option. By using the right combination of borax, soda ash and silica, gold-bearing black sands were smelted with relatively high recoveries. Earlier work done by Amankwah *et al* (2009) with several small-scale miners in Ghana shows that gold recovery via amalgamation, heating and smelting gave an average recovery of about 88% while figures for direct smelting are above 95%. In addition, direct smelting takes a shorter time to execute. The two furnaces (*sika bukya*) constructed for direct smelting application which may be powered by either liquefied petroleum gas or charcoal work well, but miners prefer the gas furnace. For a method to replace mercury amalgamation

and become widely accepted, it has to be cheap, transparent, fast, safe, and the materials utilized should be readily available. Direct smelting meets these requirements and thus has the potential to replace gold recovery by amalgamation and heating. After the fieldwork the next steps would be to highly subsidize and disseminate the technology to the small scale miners to try. Full adoption of this technology would depend on massive educational outreach.

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