Behaviour of the gold dispersed drops in the ore on being heated

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Considerable part of the world's reserves of gold is accumulated in refractory ores, which contain a dispersed gold as inclusions in sulphides and silicates. The dispersed gold extraction from refractory ores and anthropogenic objects by well-known ore-dressing methods requires a preliminary enlargement of gold parts.
Here the purpose is to analyze processes leading to a dispersed gold coarsening in the course of ore heating. The object of investigation is silicate-carbonate gold-bearing ore. Gold in the ore is associated with pyrite and arsenopyrite and is also contained in quartz and hard iron minerals. It cannot be extracted by cyanidation.
It is experimentally determined that dispersed drops of the molten gold move towards ore surface through pores under the action of thermocapillary pressure on being heated by external heat source. After the enclosing rock melting, drops of gold are floated by gas bubbles.
A condition of the drops of gold flotation in oxide melt has been analyzed. It is noted that drops of gold coagulate in the process of flotation. As a result, gold concentrates on the oxide melt surface. At the same time, the gold particles enlargement up to the sizes permissive to extract the given metal by gravity methods takes place.
Method of thin gold extraction, including material heating, melting, grinding after cooling and enrichment by gravity method with the use of a KNELSON centrifugal concentrator has been realized in laboratory conditions. This has allowed to increase the yield from 13% for an initial material to 33% after its thermal treatment, especially on narrowing the size grades of particles and on separate enrichment of the close-cut fractions. In the latter case the most part of gold is extracted by cyanidation.

Key words: dispersed gold, drops, porous bodies, interfacial tension, capillary pressure, flotation, heating.
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Introduction

Resources of free-milling gold-bearing mineral raw materials are practically exhausted. Considerable part of the world's reserves of gold is accumulated in refractory ores, which contain a dispersed gold as inclusions in sulphides and silicates. Owing to small sizes (10–20 μm), it can't be extracted by gravity methods and cyanidation. The similar problem exists in processing of anthropogenic objects containing thin gold.

That's why a great deal of efforts is recently going into the development of new approaches to processing of such ores. The most part of these new approaches are based on the following statement: to extract the dispersed gold by well-known concentration methods it is necessary to enlarge its particles. To this come a laser exposure [1, 2], microwave heating and other methods [3, 4]. Some of the methods under elaboration are patent protected [5–7].

The aim of this paper is to analyze the processes which lead to the dispersed gold enlargement in the course of ore heating.

Mechanism of coarsening the dispersed gold particles in ore on heating

The silicate-carbonate gold-bearing ore has served as a subject of inquiry. The main rockforming minerals of this ore are as follows: tiff — 45.8% (wt.), quartz — 18.5%, dolomite — 12.5%, plagioclase — 9.2%, muscovite — 5.9% and pyrite — 3.6%, sulphides (chalcopyrite, arsenopyrite and others) — less than 1%. Minor and rare minerals — iron oxides and hydroxides, such as goethite, hydrogoethite and haematite, the cumulative percentage of which amounts to 4.5%. The main valuable component is gold; its content equals to $3.6 \cdot 10^{-4}$ %. Pyrite is distributed in silicate and carbonate rocks with the fine gold associated with it. According to the phase analysis, a part of gold is presented in intergrowth with sulphides (about 13%).

To accomplish the declared aim of the work it is important that the main part of gold is presented in the used ore in a fine state (coarseness of the particles vary from submicrometers to 10 μm). It is associated with pyrite and arsenopyrite, and is also contained in quartz and hard iron minerals. It cannot be extracted by cyanidation. At the same time, the lesser part of gold (about 13%) can be treated by cyanidation.

In order to carry out the experiments on enlargement of gold particles [8], the ore has been grinded until a 0.071-mm coarseness (90%), reclaimed and extruded to cylinders 30 mm in diameter and about 1.5 mm thick. In series of experiments, gold has been added to furnace charge in the form of superfine powder with particles of size less than 1 μm to increase the gold concentration. Then the ore grinding has been carried out up to the same

size. As a result, the synthetic samples have constituted the porous bodies. The porosity has been determined by hydrostatic method. It has been ascertained that the total porosity of samples comprises not less than 30% of the prevalent open porosity, while pore sizes are close to that of the powder particles.

The extruded samples have been placed to an electric resistance furnace, preliminary heated to different temperatures. Presence and sizes of gold particles before and after heating has been checked by means of an Axio Image light microscope and a Zeiss EVO-MA 15 scanning electron microscope with an X-max console.

It is established that the particles of gold enlargement doesn't take place if gold and the rockforming minerals stay in solid state. Micron-sized drops of gold appear on the surface of samples when the temperature in furnace exceeds the gold melting temperature (1063 °C), but the extruded sample porous framework is kept safe (Fig. 1).

Gold precipitation on the surface of porous bodies can be explained in the following manner. Liquid which is presented in pores can move under the action of thermocapillary effect. Since the surface tension of gold (σ_{Au}) drops as temperature rises, then the differential capillary pressure (ΔP) arises on the ends of the liquid column in a pore during the heating process in conformity with Laplace's equation:

$$\Delta P = (2\sigma_{Au}\cos\theta)/R, \quad (1)$$

where θ — angle of moistening; R — radius of the drop surface curvature.

Liquids which don't moisten the surface of pores as gold does, will move to the area of higher temperatures (i. e. towards the surface) if a heat source is placed out of the heated body. The thermocapillary movement is possible in the process of the liquid drops heating only. After Subsequent to the temperature equalization round the drop section the pressure differential on meniscus will disappear ($\Delta P = 0$) and the liquid come to a stop.

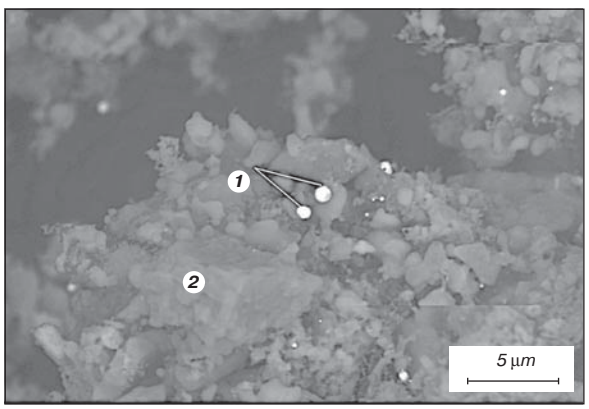

Fig. 1. The drops of gold precipitation on the ore surface after heating to the temperature of 1100 °C. The image has been obtained on a scanning electron microscope in the scattered electrons flow: *1* — drops of gold; *2* — porous matrix

To justify a possibility of the micron-sized drops of gold thermocapillary movement in porous bodies it is necessary to determine a differential temperature presence on meniscus of the drops. To specify experimentally the differential temperature on heating the particles of such a size and time of their complete warming-up is extremely hard. Therefore, heating of such particles placed to a medium with the given properties has been simulated in the present paper by application of MATLAB software package.

Asymmetric heating of a drop of gold has been guaranteed by its displacement relative to a center of the cell, simulated the medium. Systems with properties of tiff, porous tiff, quartz, soda-lime glass and platinum have been analyzed as mediums. Parabolic heat conduction differential equation (a nonstationary case) with Dirichlet boundary conditions has been solved in PDtool interactive program. Calculated were not only temperatures on the surface of particles but also heat flow directions and temperature fields in the medium and in drops of gold.

It has been found that during the heating period, a temperature gradient round the section of solid and liquid gold microparticles takes place in all mediums. An absolute value of the differential temperature on the opposite surfaces of particles (ΔT) is much greater in mediums, a heat capacity and thermal conductivity of which is closer the values innate to gold. For example, the maximal value of ΔT equals to 39.8 deg in quartz and to 1.9 deg in tiff.

Estimated time of the gold particle complete warming-up to external temperature increases as heat capacity rises parallel with the medium temperature conductivity lessening. In porous tiff this time is the highest due to the low temperature conductivity values; it amounts to 2.1 s within the temperature range from 0 to 1000 °C. Heating of a micron-sized drop of gold from 1100 °C to 1300 °C in the same medium takes 2.0 s, and maximum temperature difference on the opposite surfaces of a drop makes about 1 deg.

Hence, in the process of heating the micron-sized drops of gold located in pores, the temperature difference exists on the opposite surfaces of the drops. Even at its relatively small value ($\Delta T = 1$ deg), the surface tension force is greater than gravity. That's why drops of gold of radius less than 10^{-5} m will move to the solid body surface on heating by external heat source under the action of thermocapillary effect. For the coarse-grained drops, gravity is higher than capillary forces. Estimation of the drops of gold movement rate in a capillary according to the equitation cited in [9] shows that it is stipulated mostly by the temperature difference on meniscus rather than by their proportions. At $\Delta T = 1$ deg, the drop movement rate is of the order of 10^{-3} m/s. Since the surface tension of gold non-monotonically decreases as temperature raises, the drops of gold situated farther from the surface will move faster than that in the surface layer and can run them down. However, a likelihood of contact

and consequent coagulation of drops at low gold content in the ore is small because of considerable distances between gold particles (2.1 mm at theoretically uniform volume distribution of particles of 1 μm radius and content of 3 g/t). This is confirmed by results of the fulfilled experiments. In Fig. 1 it is obvious that drops of gold precipitated on the sample surface are of the same size as the initial particles.

At temperatures exceeding the melting temperature of enclosing rock (1300 °C) and holding for 10 min, gold distribution sharply changes. On the surface of the nascent metal-oxide melt one can observe the ball-shaped metal depositions in sizes from 1 to 50 μm, which have been absent in initial ore samples (Fig. 2). Gold is a chemically inert substance, it practically doesn't have any chemical interaction with the metal-oxide melt, an adhesion is small and angle of moistening θ is essentially greater than 90 deg. Therefore, from the standpoint of the free system energy reduction, it is more profitable for the drop of gold to contact with gas to a greater extent rather than with the metal-oxide melt, which is realized on the drops of gold precipitation on the melt surface. Mechanism of this process is the drops of gold flotation by gas bubbles (CO_2 and SO_3 in our case). Carbon and sulfur oxides are generated as a result of thermal decomposition of carbonates and sulphides which are contained in the origin silicate-carbonate ore.

On considering the flotation condition which provides the interfacial tension forces excess over gravity, the surface tension on a liquid — gas phase boundary is usually analyzed [10]. This approach is also correct for a solid body – liquid – gas phase boundary. Two liquids and gas are present during the drops of molten gold flotation. In that case to establish equilibrium along the moistening perimeter, a geometric sum of all three tension vectors (σ_{Au-m} on a gold — metal-oxide melt phase boundary, σ_{Au-g} on a gold – gas phase boundary, σ_{m-g} on a metal-oxide melt — gas phase boundary) should be equal to zero. The curvature radii of upper (at the border with gas) and bottom surface (at the border with melt) of floating drop will be different due to the difference of capillary pressures (see Equation 1). It should be also taken into account that pressure at the bottom surface is heightened in comparison with gas pressure by the value of the metal-oxide melt column mains pressure. As a result, the shape of drop is disfigured.

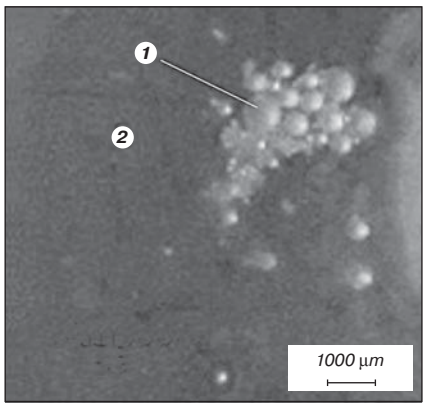

Fig. 2. Large drops of gold on the surface of the molten sample of silicate-carbonate ore after heating to the temperature of 1300 °C: *1* — drops of gold; *2* — porous matrix

To write down a flotation condition it is necessary to analyze absolute values of all the tensions mentioned above. According to the literature data [8, 9, 11], we have two high tensions, namely $\sigma_{Au-m} = 1450$ mJ/m^2, $\sigma_{Au-g} = 1100$ mJ/m^2, and one small $\sigma_{m-g} = 500$ mJ/m^2. In our case, tension triangle is an acute-angled one and angle of moistening θ is close to 140 deg. This implies that the drop of gold surface fracture at a three-phase border will not be as big. Gold – gas surface is moderately different from the gold – metal-oxide melt surface extension. Then the tension scheme will be moderately different from the case of solid gold and flotation condition can be written as:

$$2\pi R\sigma_{m-g}\cos\theta > 4/3\pi R^3 g(\rho_{Au} - \rho_m), \quad (2)$$

where ρ_{Au}, ρ_m — density of gold and metal-oxide melt, respectively; σ_{m-g} — interfacial tension at the metal-oxide melt — gas boundary.

Equation 2 holds true for drops of gold of radius $R = 1–100$ μm.

Drops of gold will be floated by gas bubbles if the following inequality takes place:

$$V_g\rho_m > V_{Au}\rho_{Au}, \quad (3)$$

where V_g, V_{Au} — volume of a bubble and a drop of gold, respectively.

Density of gold is about 8 times greater than density of the metal-oxide melt.

Hence, radius of gas bubbles which float drops of gold should be at least two times more than that of the latter. Examination of the metal-oxide melt photomicrography after the heating up to 1300 °C has showed presence of bubbles of 750 μm radius, which is enough for floating even the most coarse drops of gold in conformity with Equation 2. It is important to note that if the probe of an origin ore is pretreated by acetic acid for the purpose of carbonates eliminating whereupon it is melted, than gold on the melt surface will not appear. This confirms the determinative role of flotation for gold precipitation on the melt surface.

Conclusion

As is evident from the foregoing, the dispersed drops of gold move towards ore surface through pores under the action of thermocapillary pressure during the process of heating by external heat source. After the enclosing rock melting, drops of gold are floated by gas bubbles. Coagulation takes place in the process of flotation. As a result, gold reducing occurs on the surface of generated metal-oxide melt

and coarsening of particles up to the size enabling to extract gold by gravity methods happens.

Using refractory silicate-carbonate ores as an example, method of thin gold extraction, including material heating, melting, grinding after cooling and enrichment by gravity method with the use of a KNELSON centrifugal concentrator has been realized in laboratory conditions. This has allowed to increase the yield from 13% for an initial material to 33% after its thermal treatment, especially on narrowing the size grades of particles and on separate enrichment of the close-cut fractions. In the latter case the most part of gold is extracted by cyanidation.

According to experimental data of the Uralmekhnabor JSC, a preliminary technical and economic assessment of the presented approach has been fulfilled in comparison with technology of gold ultrafine grinding and consequent leaching as a way of refractory noble metals concentrates processing [12] (pressure and bacterial leaching are characterized by even greater capital outlays). The estimation has brought out the following. Heat treatment realization will require a third less additional capital outlays. Through gold extraction is about 16% higher which can lead to a proportional increase in the finished commodity manufacturing (~17%) as well as in annual receipt. Since one of the main expense items in the method under consideration is energy consumption on material heating and melting, its realization is worthwhile in the first place for processing restricted by weight anthropogenic objects bearing fine gold.

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