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Using Kerosene as an Auxiliary Collector to Recover Gold from Refractory Gold Ore Based on Mineralogical Characteristics

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Abstract: Carbon–arsenic-bearing gold ore is a typical complex refractory gold resource. Traditionally, xanthate was often used as a flotation agent to separate gold minerals. But, in this paper, in order to reduce the cost of the agent, kerosene was used as an auxiliary collector, and the gold grade and recovery rate were increased by about 10 g/t and 5.5%, respectively. Through process mineralogy studies of the raw ore, it was found that the ore has an Au grade of 5.68 g/t, most of which is surrounded by sulfide ore, accounting for 79.46%. The main minerals are pyrite, arsenopyrite, and quartz, etc. Their content, shape, particle size distribution, and occurrence state were obtained via microscopic observation and statistical analysis. According to the results of process mineralogy, various flotation conditions were tested, including grinding fineness, kerosene dosage, collector dosage, foaming agent dosage, and the slurry pH value. The optimal chemical system and the process flow of “two roughing, three cleaning and two scavenging” were finally determined, and the concentrate product with a gold grade of 42.83 g/t and recovery of 91.02% was obtained, which verified the feasibility of the kerosene-assisted xanthate flotation of refractory gold.

Keywords: kerosene; flotation; refractory gold; auxiliary collector; process mineralogy



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1. Introduction

Gold is an important precious metal, a trace element, with excellent (stable) chemical and physical properties; it has a wide range of applications in electronic products, jewelry, equipment manufacturing, finance, and other fields, affecting the world’s economic development, industrial production, and financial order [1–5]. According to these data, as of 2022, China’s official gold reserves totaled 2964.37 tons, and with the continuous development of science, more and more gold still needs to be mined to meet the needs of production and life [6,7].

At present, due to the continuous exploitation and utilization of gold mines, high-quality gold ore resources have been gradually depleted, and low-grade complex refractory gold ore has gradually begun to become the focus of attention. At present, there is no unified standard for the classification of refractory gold ores, but according to the mineralogical analysis of minerals, refractory minerals can be mainly divided into the following three categories: (1) complex polymetallic gold sulfide ore, (2) gold carbide ore, and (3) gold telluride. The main reason for refractory gold mines is that gold is wrapped in sulfide ores or the leached gold is adsorbed by organic carbon and other substances in these minerals, resulting in a “gold robbing” phenomenon, which affects the recycling of gold [8–14]. So arsenic-carbon-containing gold sulfide ore is one of the most difficult gold ores to treat at present, and it is also an important gold ore resource in China.

Sitando et al. [15] found that the “gold-robbing” abilities of different types of “gold-robbing” substances are significantly different. Quartz only adsorbed 1.7% of the gold,

kaolinite, and hematite adsorbed about 18% of the gold, while pyrite sulfides and carbonaceous materials, which are highly “gold-robbing”, absorbed all gold within half an hour. Therefore, for complex and refractory gold mines, the ore is generally pretreated to eliminate the influence of unfavorable factors on leaching in the gold ore by changing the physical and chemical properties of the ore so as to obtain the best leaching rate. However, the pretreatment process requires high-pollution and high-energy consumption processes, such as roasting, and the leaching process also requires a large number of highly toxic substances, such as cyanide, which greatly damages the environment [16–19]. Therefore, it is an effective separation method to enrich the target minerals using flotation reagents through beneficiation technology, increasing the gold grade in the concentrate and greatly reducing the use of cyanide and energy consumption [20,21].

Since most of the gold is embedded in sulfide ores, gold extraction can be achieved using flotation sulfides. The commonly used flotation agent is generally xanthate, but in actual production, xanthate also has the shortcomings of a high price and strong pollution. Moreover, the carbon in the gold ore has adsorbability to the collector [22]. Therefore, in order to reduce the amount of xanthate, in the flotation industry experiment, a more economical agent is often selected, and useful minerals are recovered collaboratively through a combination of drugs to achieve the purpose of reducing costs [23–26]. Kerosene has received a lot of attention in recent years as a common flotation collector and auxiliary collector, and some studies have shown that kerosene can have a synergistic effect with the sulfide ore collector to improve the recovery rate of gold [22,27–29].

Therefore, in order to solve the problems of environmental pollution and the high cost of the collector in the process of the flotation of refractory gold ores, a flotation separation test was carried out on a carbon-containing arsenic-containing sulfide refractory gold mine in Fengcheng, China, using kerosene combined with xanthate; the appropriate separation process flow and agent system were created. And a detailed process mineralogy study was carried out on the mineral in order to maximize the understanding of the ore properties and provide a theoretical basis for the determination of the beneficiation process.

2. Materials and Methods

2.1. Samples

The samples used in this test were from Huifeng Mining Co., Ltd., Fengcheng, China. crushed to -2 mm with a double roll crusher and thoroughly mixed as test raw materials. Table 1 shows the chemical composition of the raw ore. It can be seen from Table 1 that the content of Au in the raw ore is 5.68 g/t, and the main oxides are SiO_2 and Al_2O_3 , the contents of which are 58.28% and 14.51%, respectively. The proportion of S is 3.90%, and the harmful elements of C and As are 1.02% and 0.364%, respectively. The X-ray diffractometry (XRD) analysis in Figure 1 shows that the main minerals of the ore are muscovite, quartz, and pyrite, and the content of gold minerals is very low.

Table 1. Chemical composition analysis results of raw minerals (%).

Elements	Au (g/t)	Ag (g/t)	TFe	SiO_2	Al_2O_3	CaO
Content/%	5.68	8.76	5.08	58.28	14.51	2.22
Elements	MgO	As	Pb	S	C	
Content/%	2.35	0.364	0.011	3.90	1.02	

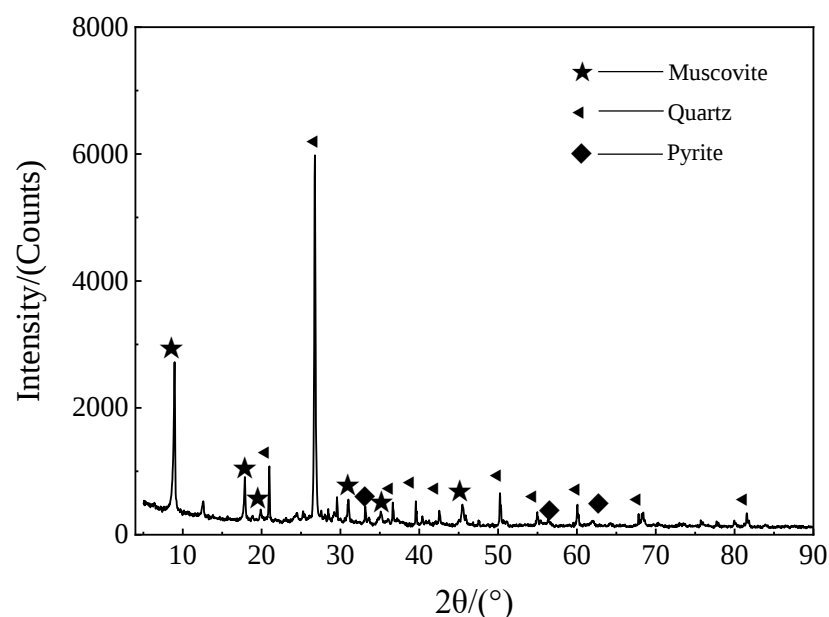


Figure 1. X-ray diffraction spectra of the raw minerals.

2.2. Mineral Technology Methods

The primary phase determination of gold minerals was carried out using XRD and the chemical multielement method. The ore was mixed with resin to achieve polished slices, and the composition of the raw ore was observed via an optical microscope (DM6000 M, Leica, Wetzlar, Germany). The structural characteristics and occurrence state of metal minerals and gangue minerals were determined using the Mineral Liberation Analyser (MLA250, FEI, Brno, Czech Republic) and Scanning Electron Microscope (Quanta 250, FEI, Brno, Czech Republic) analysis of the raw ore grinding products.

2.3. Flotation Methods

After grinding the ore sample to the required fineness, the flotation test was carried out in the XFGII aerated hanging cell flotation machine; after adjusting the required pH, according to the amount required for each test, the auxiliary collector kerosene, the activator copper sulfate, the collector xanthate and the foaming agent terpenic oil (2[#] oil) were added in turn, and the flotation time and the amount of agent added are displayed in the flow chart of each conditional experiment. The foam product and the product in the tank were filtered separately, dried, and weighed, and samples were taken to analyze the gold grade and calculate the recovery rate. After the ore was analyzed via process mineralogy, grinding and flotation were carried out. The research roadmap is shown in Figure 2a. The flotation process of “two roughing, two cleaning and two scavenging” was initially adopted in the test (Figure 2b). The optimal dosage of the collector, foaming agent, and others was determined according to the recovery rate and grade of the concentrate. And under the best dosage, according to the grade and recovery rate of the obtained concentrate, it was determined whether to increase or reduce the amount of roughing, cleaning, scavenging, and obtain the final process. Generally, when the grade was not satisfied, the number of cleanings could be increased.

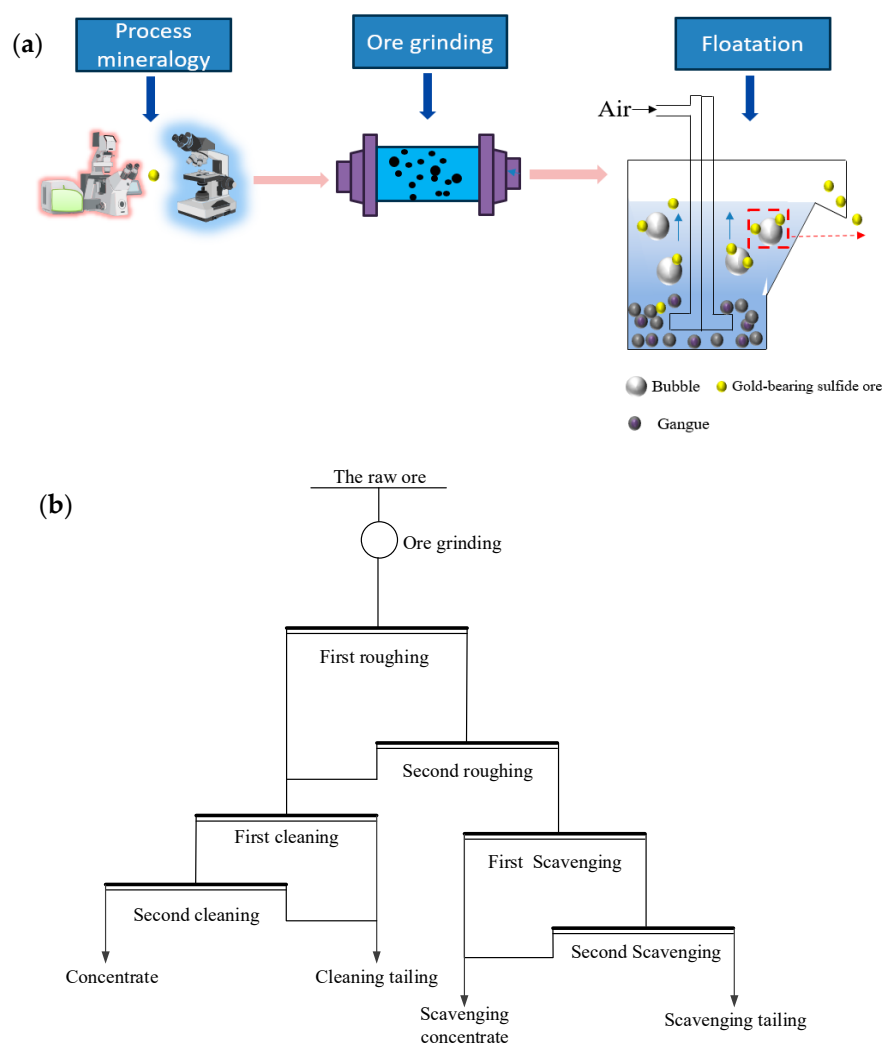


Figure 2. (a) Research schematic diagram and (b) flotation process flow chart.

3. Results

3.1. Ore Components and Mineral Characteristics

The main mineral content of the gold ore is shown in Figure 3. The sulfide ore is dominated by pyrite, followed by arsenopyrite. The percentage of the mineral mass contents is 8.94% and 1.05%, respectively. It also contains trace amounts of chalcopyrite and sphalerite. The main gangue minerals in the ore are quartz and muscovite, with mass fractions of 35.68% and 36.13%, respectively. In addition, it contains a small amount of biotite, carbonate minerals, feldspar, chlorite, and so on.

3.1.1. Gold

The Au content of the gold mine is 5.68 g/t, and all the gold-bearing minerals found in the ore are natural gold. The gold particles observed under the optical microscope are shown in Figure 4a–c, mainly in the form of wheat grains, followed by needle- and leaf-shaped particles. The gold particles observed via a scanning electron microscope are shown in Figure 4d. The short diameter of the natural gold is 1.600 μm , the long diameter is 3.751 μm , and the elongation is 2.34. Monomer gold is angular granular and not connected to other minerals. The distribution size of natural gold is very small and is distributed between 0.001 mm and 0.01 mm. Among them, 0.01~0.005 mm accounted for 71.42%, and 0.005~0.001 mm accounted for 28.58%.

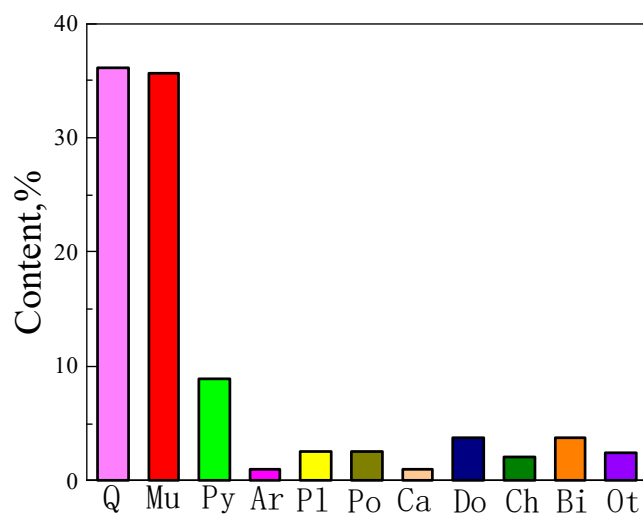


Figure 3. Mineral mass fraction of the gold ore. (Q-quartz, Mu-muscovite, Py-pyrite, Ar-arsenopyrite, Pl-plagioclase, Po-potash feldspar, Ca-calcite, Do-dolomite, Ch-chlorite, Bi-Biotite, Ot-others).

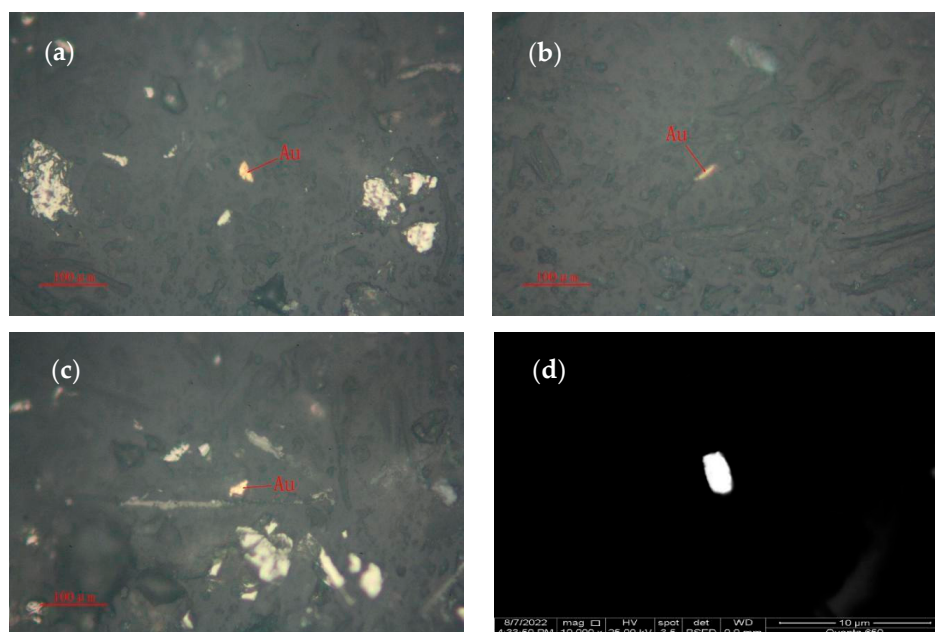


Figure 4. Occurrence state of gold particles in gold mine. (a–c) Natural gold monomer particles; (d) Backscattered gold monomer particles.

The results of the phase analysis of Au are shown in Table 2. The gold particles in the ore are mostly covered by metal minerals and gangue minerals. Wrapped gold accounted for 96.43%, and naked and semi-naked gold accounted for 3.57%. The gold coated using sulfide was the main gold, accounting for 79.46%, so the beneficiation method mainly recovered gold by recovering the sulfide ore. It was followed by carbonate-coated gold, brown iron-coated gold, and silicate-coated gold, accounting for 3.13%, 3.87%, and 9.97%, respectively.

Table 2. Results of phase analysis of Au.

	Nudity and Semi-Exposed Gold	Carbonate Coated Gold	Brown Iron Coated Gold	Sulphide Coated Gold	Silicate Coated Gold	Total
Content/ $\text{g} \times \text{t}^{-1}$	0.24	0.21	0.26	5.34	0.67	6.72
Occupancy/%	3.57	3.13	3.87	79.46	9.97	100.00

3.1.2. Pyrite

Pyrite is the main metallic mineral in ores, with a relatively high content. Under the microscope, pyrite mostly shows an idiomorphic and semi-idiomorphic granular structure, and a small amount shows a sheet and rod-like structure, Figure 5a–d. The main disseminated structure is distributed in the gangue, Figure 5e, and a small amount of pyrite aggregates are distributed in the gangue in a striped manner, Figure 5f. A graphite-filling distribution, Figure 5g,h, is common at the edges with intergranular and pores of pyrite, and graphite has a negative effect on the flotation process. Combined with MLA (Figure 6) and SEM (Figure 5i,j), it can be seen that some pyrite is closely associated with other metal minerals, and the monomer pyrite is coated with a small amount of quartz and arsenopyrite, while the coated pyrite is mainly coated with quartz, muscovite, and other minerals.

As can be seen from Figure 7, the distribution size of pyrite in flotation minerals is very fine, with a $-75 \mu\text{m}$ particle content accounting for 98.33% and a $-38 \mu\text{m}$ content for 79.11%. The average content of Fe in pyrite is 46.80%, which belongs to high sulfur iron-poor pyrite. It generally contains a small amount of As, with an average content of 1.76%.

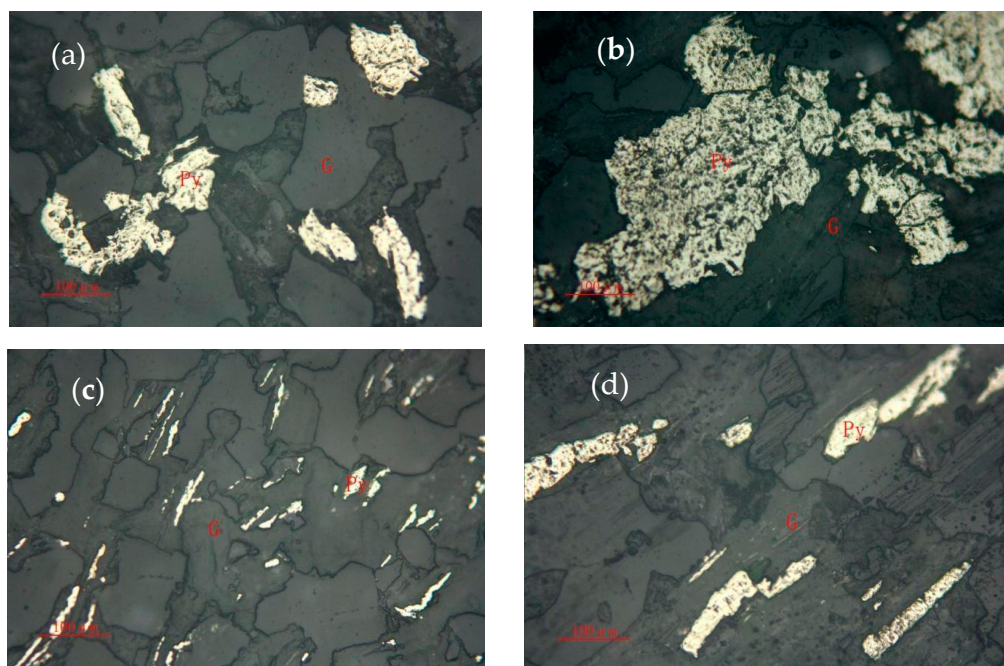


Figure 5. Cont.

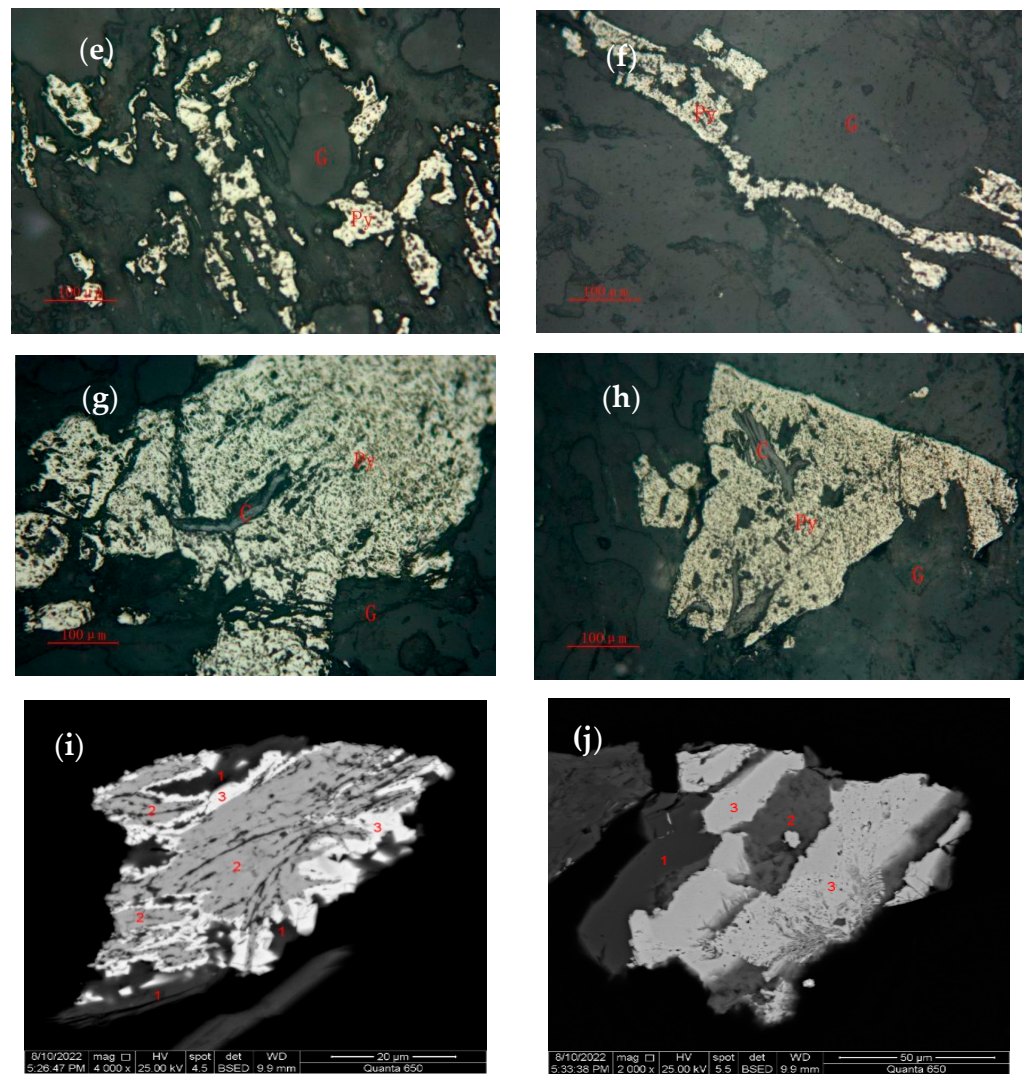


Figure 5. Microtopography of pyrite in gold mine. (a) Fine grained pyrite; (b) Hemidiomorphic pyrite; (c) Fine flaky pyrite; (d) Rod pyrite; (e) Disseminated pyrite; (f) Striped pyrite; (g,h) Carbon is filled with pyrite; (i) Pyrite, arsenopyrite and Muscovite are closely connected; (j) Pyrite is associated with quartz and chlorite ((i)—1-muscovite, 2-pyrite, 3-arsenopyrite) ((j)—1-quartz, 2-chlorite, 3-pyrite) (G-gangue).

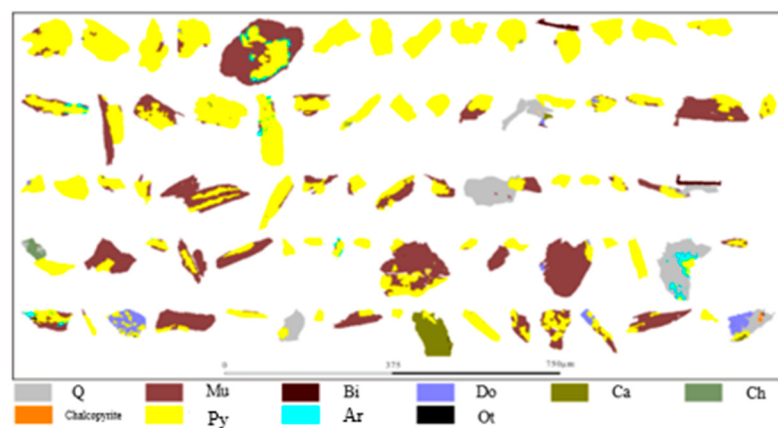


Figure 6. Diagram of dissociation and the associative relationship of pyrite (MLA of pyrite).

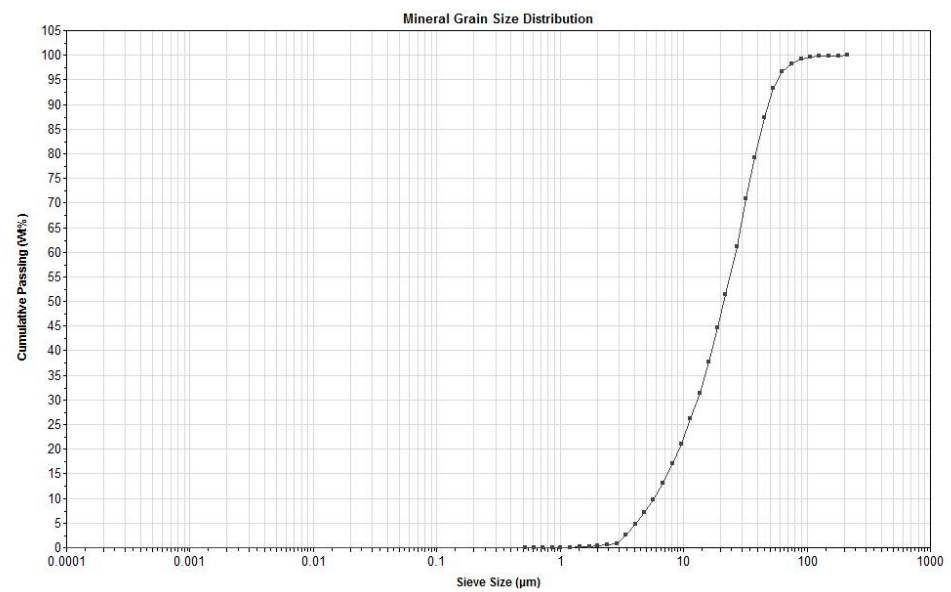


Figure 7. Pyrite size distribution map.

3.1.3. Arsenopyrite

Arsenopyrite is the main source of arsenic in raw ore. As shown in Figure 8, the results of the microscope show that arsenopyrite is mainly distributed in gangue in the form of the granular, rhomboid, spear, and needle. Arsenopyrite and pyrite are adjacent and crystalline symbiosis, and the boundary between arsenopyrite and pyrite is not obvious, while some arsenopyrite is colloidal around pyrite. As can be seen from the SEM of arsenopyrite (Figure 8e,f), the arsenopyrite is coated with a small amount of quartz, and the wrapped arsenopyrite is mainly coated with quartz, muscovite, pyrite, and other minerals.

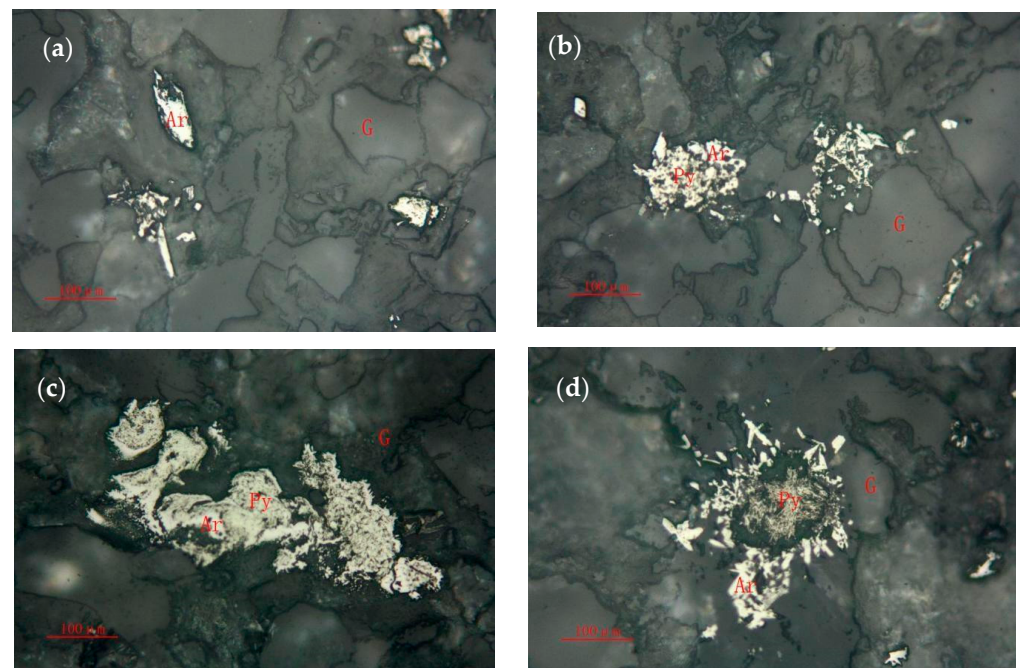


Figure 8. Cont.

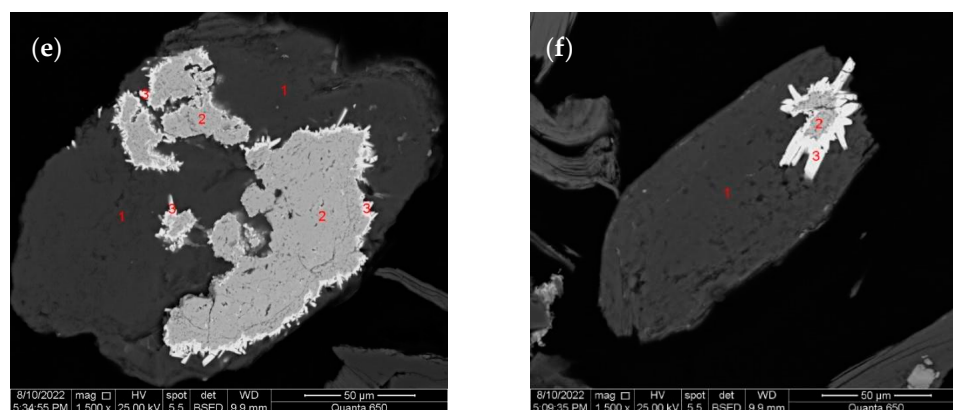


Figure 8. Microtopography of arsenopyrite in gold mine. (a) Fine grained arsenopyrite; (b,c) Pyrite is associated with arsenopyrite; (d) Arsenopyrite is around the pyrite; (e) Arsenopyrite is connected with Muscovite; (f) Arsenopyrite is coated with pyrite ((e)—1-muscovite, 2-arsenite) ((f)—1-muscovite, 2-pyrite, 3-arsenopyrite) (G-gangue).

3.1.4. Carbon

Carbon is mainly produced in flake aggregates; flake crystals are often curved and dispersed in gangue (G), and the particle size is not uniform (Figure 9a). Some of the carbon is in contact with pyrite particles and is filled in the intergranular and pore spaces of pyrite (Figure 9b). The results in Table 3 show that the carbon in the raw ore is mainly organic carbon, accounting for 45.10%, while the carbon and graphitic carbon in carbonate account for 26.47% and 28.43%, respectively.

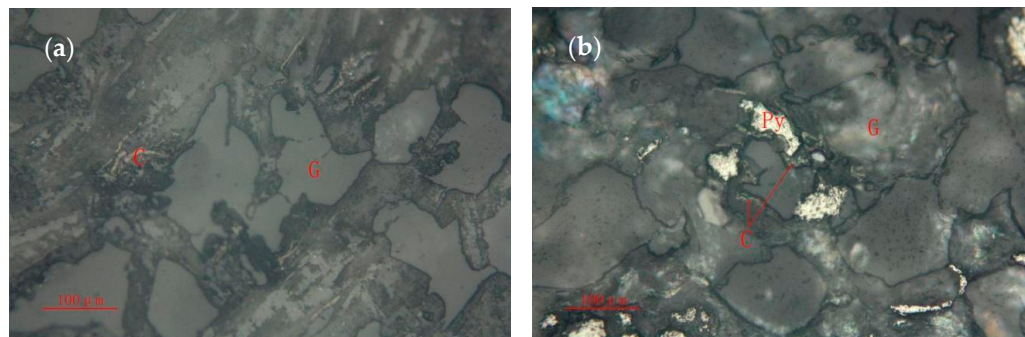


Figure 9. Microtopography of carbon in gold mine. (a) Microflake carbon; (b) Carbon is distributed between pyrite and gangue mineral.

Table 3. Results of phase analysis of C.

	Carbon in Carbonate	Organic Carbon	Graphite Carbon	Total Carbon
Content/%	0.24	0.21	0.26	5.34
Occupancy/%	3.57	3.13	3.87	79.46

3.1.5. Quartz

Quartz is mainly produced in idiomorphic and semi-idiomorphic granular aggregates with fine and uniform particle sizes. Quartz is associated with feldspar, muscovite, biotite, amphibole, and other minerals, and the grains are filled with sericite carbonate minerals, and some fine quartz is embedded in the sericite aggregate (Figure 10).

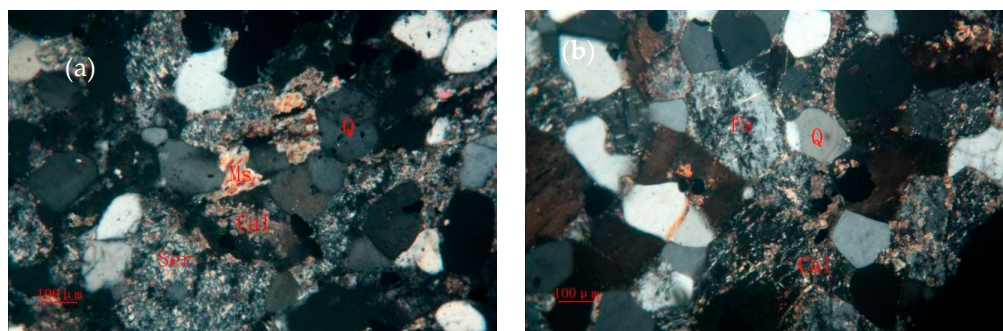


Figure 10. Microtopography of quartz in gold min. (a) Quartz (Q) associated with muscovite (Ms) and sericite (Ser) (b) Feldspar (Fs) and quartz (Q) symbiosis, intergranular and pore filled with carbonate minerals (Cal).

3.2. Flotation Tests

3.2.1. Grinding Fineness Condition Test

Firstly, the beneficiation process of “two roughing, two cleaning and two scavenging” was designed in order to preliminarily explore the beneficiation index. The natural pH of the slurry and the dosage of kerosene were set to 1600 g/t, the dosage of copper sulfate was 400 g/t (First roughing 200 g/t, Second roughing 200 g/t), and the dosage of isoamyl xanthate was 300 g/t (Fr, Sr 100 g/t, First scavenging, Second scavenging 50 g/t), the total dosage of foaming agent 2# oil was 160 g/t (Fr, Sr 50 g/t, Fs, Ss 30 g/t). The influence of grinding fineness of -0.074 mm on the flotation index of 50%, 60%, 70%, 80%, 85% and 90% was investigated, the test process is shown in Figure 10, and the test results are shown in Figure 11.

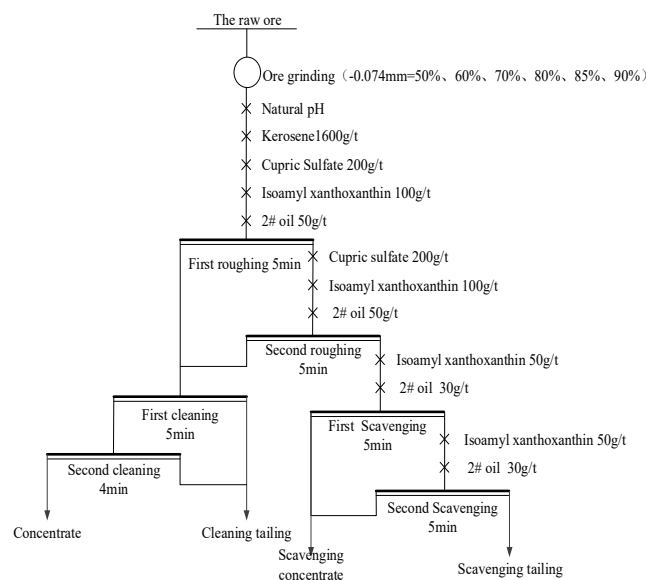


Figure 11. Test flow of grinding fineness condition.

The results in Figure 12 show that with the increase in the grinding fineness, the Au grade in the concentrate showed an increasing trend, while the Au recovery rate showed a decreasing trend. When the grain size of the grinding product was fine, the gold mineral in the ore was better when dissociated from gangue minerals, and the Au grade of the concentrate increased. However, due to the fine grinding, the difference between the concentrate and tailings was not obvious, and the gold-bearing minerals in the ore were lost in the tailings, which could not be effectively recovered, resulting in a low recovery rate [30,31]. When the fineness of the grinding product increased from 80% to 90% and from -0.074 mm, the Au grade in the concentrate increased from 40.34 g/t to 41.17 g/t, and

the Au recovery rate decreased from 63.98% to 59.53%. The Au grade in the concentrate could not be greatly improved, and the recovery rate decreased by 4.45%. The influence of grinding fineness on the concentrate index was comprehensively analyzed, and the appropriate grinding fineness was determined to be -0.074 mm, which accounted for 85%.

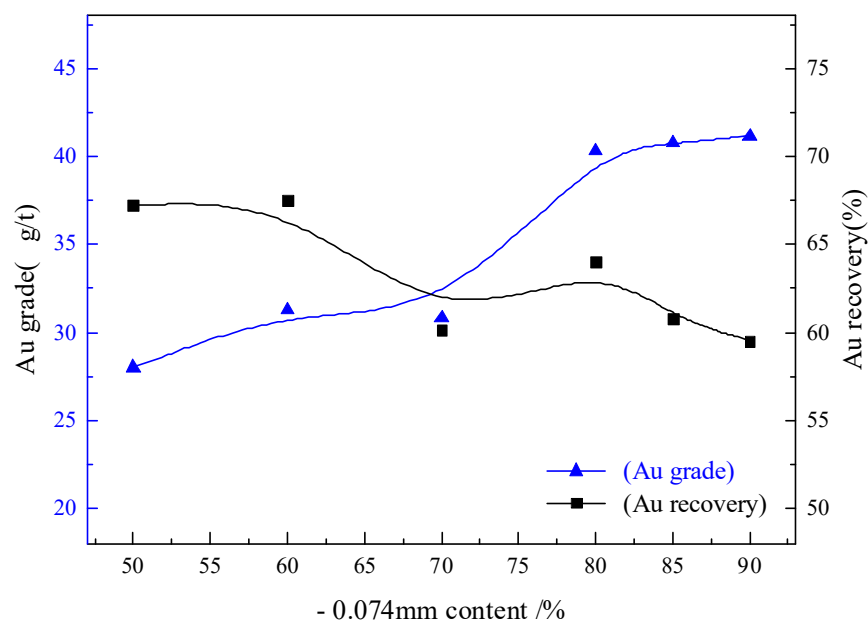


Figure 12. Influence of grinding fineness on Au separation index in the concentrate.

3.2.2. Kerosene Dosage Condition Test

As the flotation effect was good, the previous flotation process continued to carry out conditional tests. Under the condition that the fineness of grinding was 85% -0.074 mm, with the natural pH of the pulp, the total amount of copper sulfate was 400 g/t (Fr 200 g/t, Sr 200 g/t), the total amount of isoamyl xanthate was 300 g/t (Fr, Sr 100 g/t, Fs, Ss 50 g/t), and the total amount of 2# oil was 160 g/t (Fr, Sr 50 g/t, Fs, Ss 30 g/t). Kerosene consumption was selected as 800 g/t, 1200 g/t, 1600 g/t, 2000 g/t, and 2400 g/t, respectively, to investigate the influence of kerosene consumption on the flotation indexes. The test process is shown in Figure 13, and the test results are shown in Figure 14.

Figure 14 shows that with the increase in kerosene consumption, the Au grade and recovery rate in the concentrate gradually increased. When the kerosene consumption increased from 800 g/t to 2000 g/t, the Au grade in the concentrate gradually increased from 39.89 g/t to 49.41 g/t, and the Au recovery rate gradually increased from 55.44% to 61.18%. When the kerosene consumption was further increased to 2400 g/t, the Au grade in the concentrate was almost unchanged, and the Au recovery rate increased to 65.64%. The results show that the addition of kerosene improved the surface properties of sulfide ore, enhanced the adsorption of the collector to sulfide ore, and produced a synergistic effect [27,32]. The influence of kerosene consumption on the concentrate index and economic benefit was analyzed comprehensively, and the appropriate kerosene consumption was determined to be 2000 g/t.

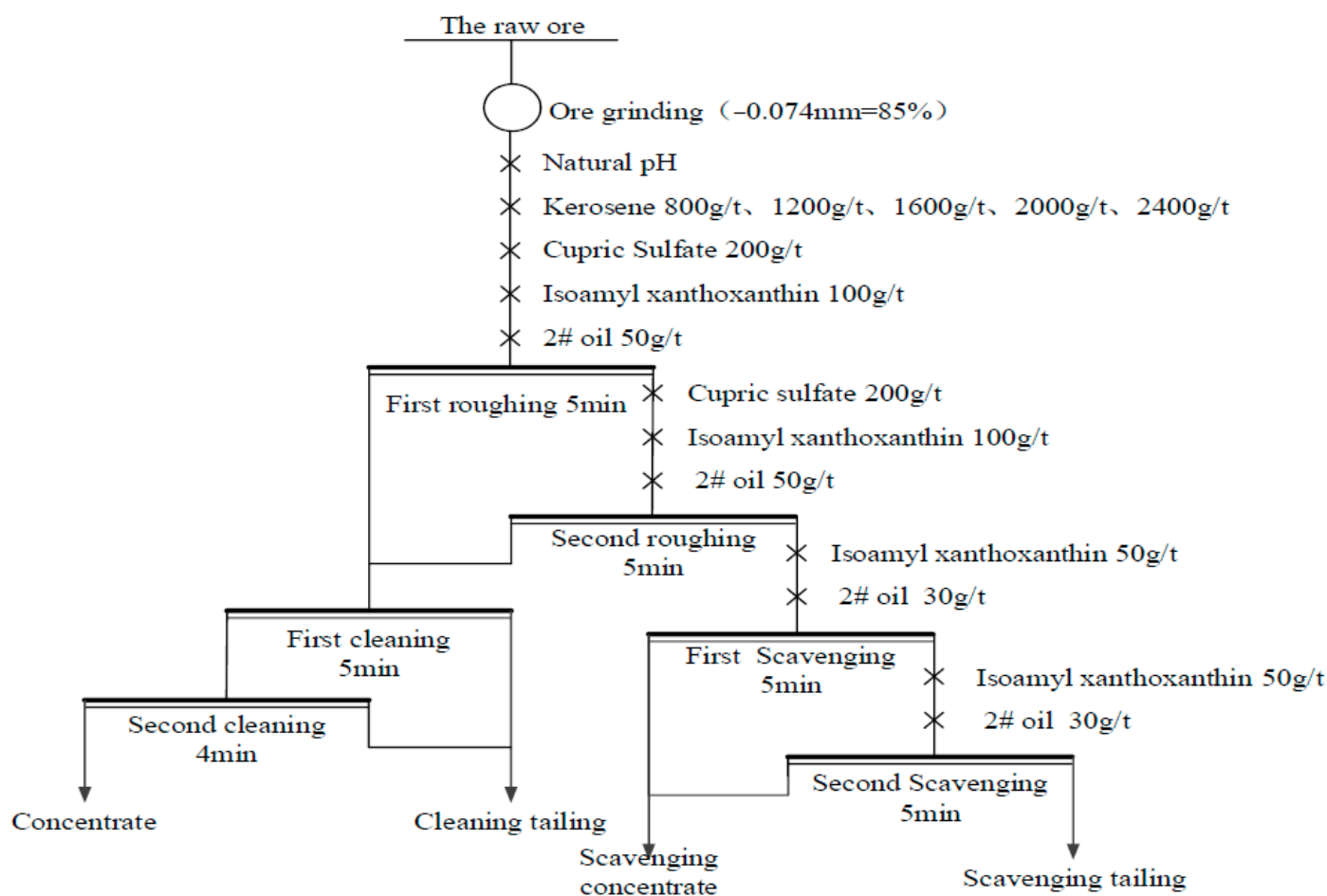


Figure 13. Kerosene dosage condition test flow.

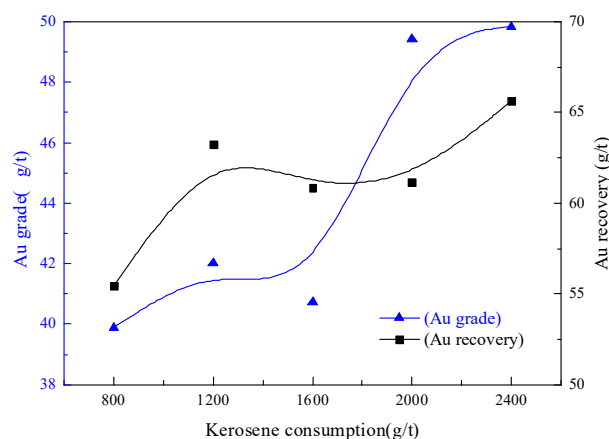


Figure 14. Influence of kerosene dosage on Au separation index in the concentration.

3.2.3. Activator Dosage Condition Test

Under the conditions of the fineness of grinding at -0.074 mm, accounting for 85% of the natural pH of the pulp, the dosage of kerosene was 2000 g/t, the dosage of isoamyl xanthate was 300 g/t (Fr 100 g/t, Sr 100 g/t, Fs 50 g/t, Ss 50 g/t), and the dosage of 2# oil was 160 g/t (Fr and Sr 50 g/t, Fs and Ss 30 g/t), The dosage of the selected activator copper sulfate was 300 g/t (Fr 100 g/, Sr 200 g/t), 400 g/t (200 g/t, 200 g/t), 500 g/t (300 g/t, 200 g/t), 600 g/t (400 g/t, 200 g/t), and 700 g/t (500 g/t, 200 g/t) to investigate the effect

of copper sulfate dosage on the flotation index. The test process is shown in Figure 15, and the results are shown in Figure 16.

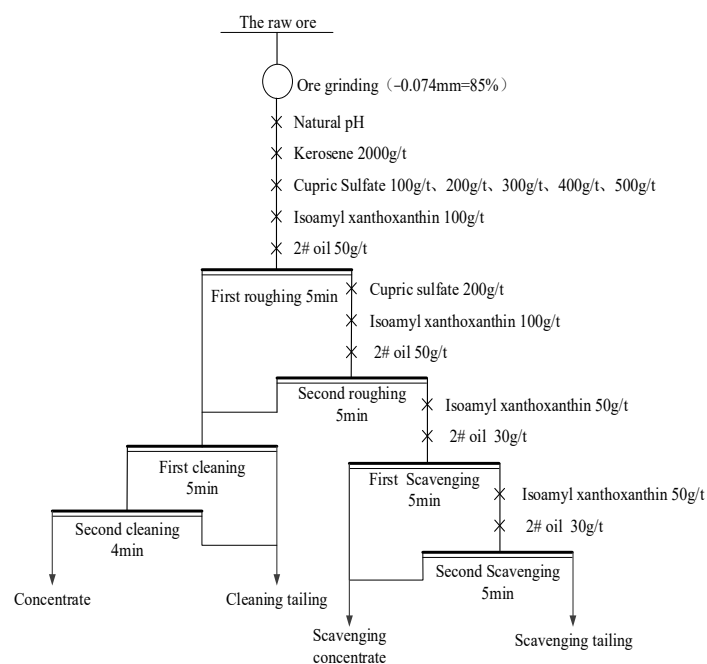


Figure 15. Active agent dosage condition test flow.

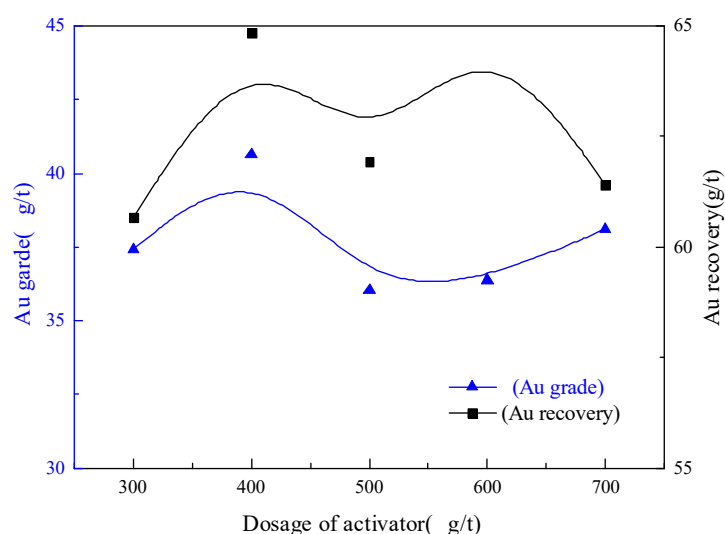


Figure 16. Influence of activator dosage on Au separation index in concentration.

The results in Figure 16 show that with the increase in the amount of activator, the Au grade in the concentrate firstly increased and then decreased, and then tended to be stable. There was no significant change in the Au recovery rate. When the amount of activator copper sulfate was 400 g/t, the concentrate obtained had the highest Au grade of 40.64 g/t. The influence of the amount of copper sulfate on the concentrate index was analyzed comprehensively, and the appropriate amount of copper sulfate was determined to be 400 g/t.

3.2.4. Pulp pH Condition Test

This section intends to adjust the pH of the pulp by adding sulfuric acid and sodium carbonate and then investigate the influence of the pH of the pulp on the sorting index.

Under the condition that the grinding fineness was -0.074 mm, accounting for 85%, the amount of kerosene was 2000 g/t, the amount of copper sulfate was 400 g/t (Fr 200 g/t, Sr 200 g/t), the amount of isoamyl xanthate was 200 g/t (Fr and Sr are 100 g/t), and the amount of 2# oil was 100 g/t (Fr and Sr are 50 g/t). The dosages of sulfuric acid and sodium carbonate were selected as 1000 g/t and 200 g/t, respectively, to investigate the effect of the dosages of sulfuric acid and sodium carbonate on the flotation index. The test process is shown in Figure 17, and the results are shown in Figure 18.

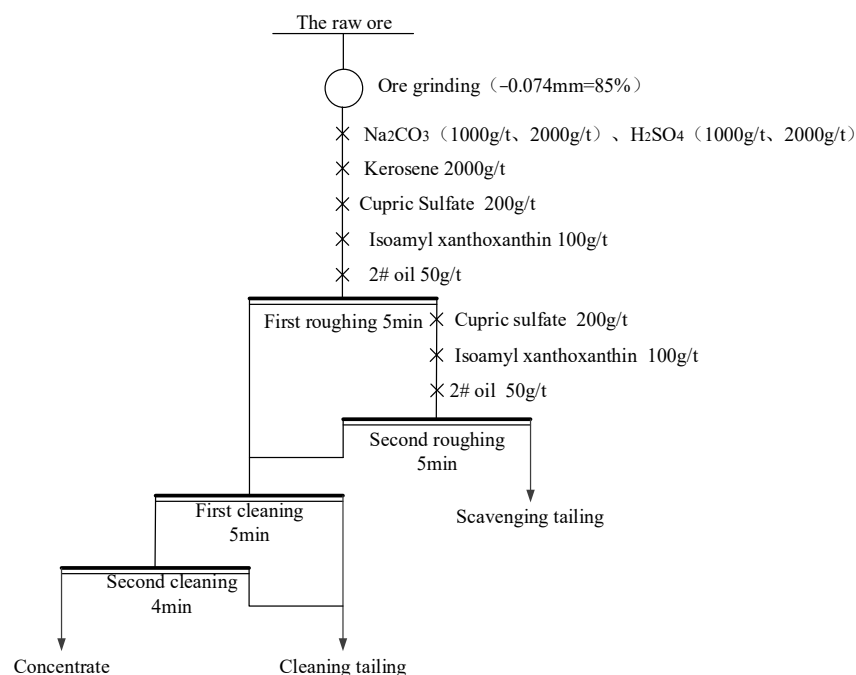


Figure 17. pH condition test flow.

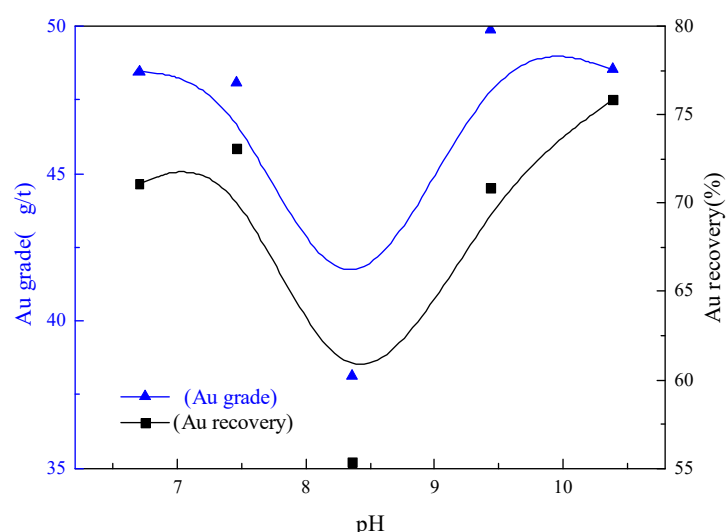


Figure 18. Influence of pH on Au separation index in concentration.

The results in Figure 18 show that with the increase in the pulp's pH value, the Au grade and Au recovery in the concentrate generally showed a trend of first decreasing and then increasing. When the pulp's pH was 9.44, that is, the amount of sodium carbonate was 1000 g/t, the Au grade in the concentrate reached the maximum, which was 49.85 g/t, and the Au recovery was 70.84%. In addition, sodium carbonate is a good dispersant to prevent the agglomeration of fine mud in the pulp and improve the selectivity of the flotation

process [33,34], so it is determined that the adjustment agent of sodium carbonate could be added to the pulp at 1000 g/t.

3.2.5. Collector Dosage Condition Test

In order to test the efficiency and save costs, the flotation effect can be reflected according to the roughing index. As a grinding fineness of $-0.074\text{ mm}=85\%$, the sodium carbonate dosage was 1000 g/t, kerosene dosage was 2000 g/t, copper sulfate dosage was 400 g/t (Fr 200 g/t, Sr 200 g/t), and 2# oil dosage was 100 g/t (Fr 50 g/t, Sr 50 g/t). The dosage of isoamyl xanthate as the collector was 100 g/t (Fr 50 g/t, Sr 50 g/t), 150 g/t (75 g/t, 75 g/t), 200 g/t (100 g/t, 100 g/t), 250 g/t (125 g/t, 125 g/t), 300 g/t (125 g/t, 125 g/t), respectively. Under the conditions of 300 g/t (150 g/t, 150 g/t), the influence law of the amount of the collector on the flotation index was investigated. The test process is shown in Figure 19, and the results are shown in Figure 20.

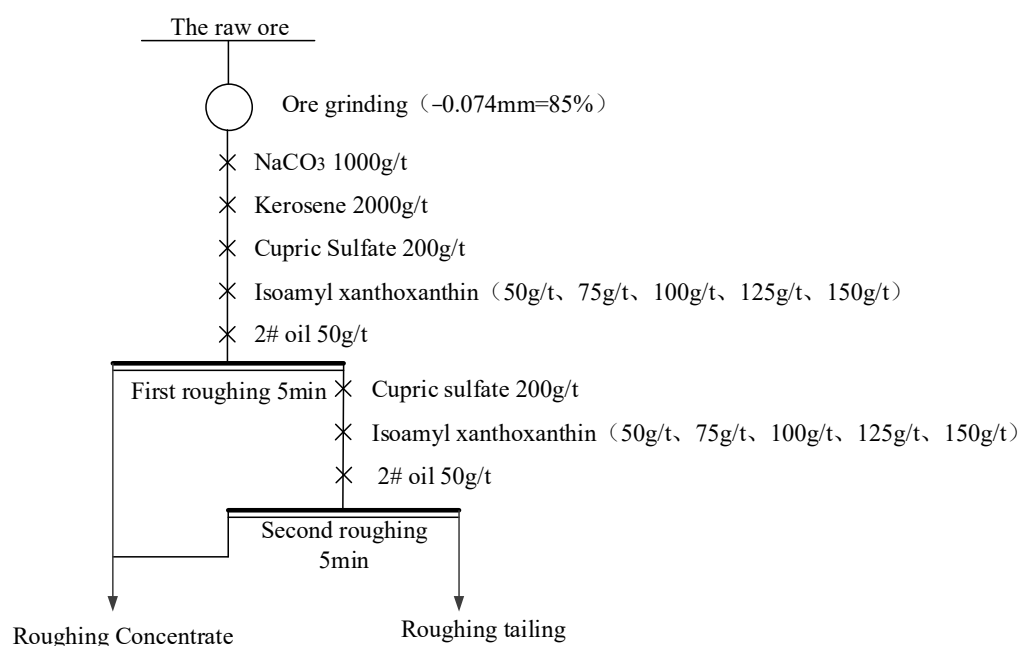


Figure 19. Collector dosage condition test flow.

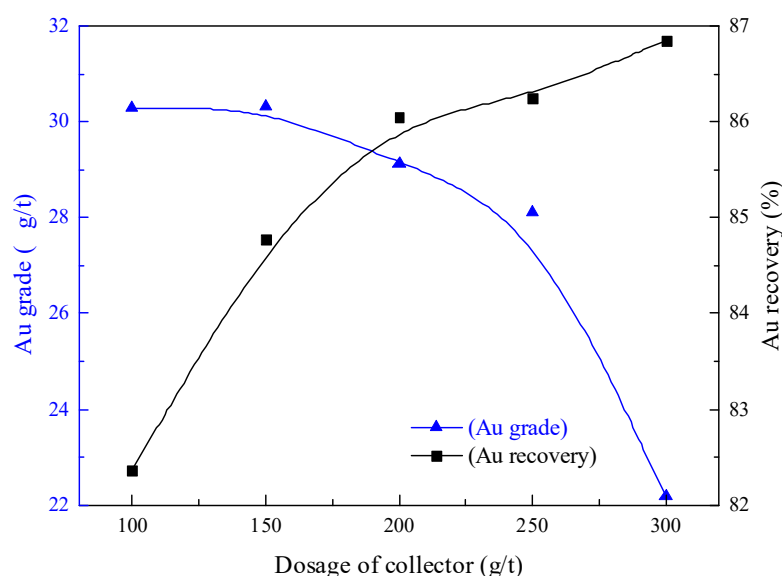


Figure 20. Influence of collector dosage on Au separation index in the concentration.

Figure 20 shows the influence of the amount of collector on the Au index for the coarse concentrate. It can be seen from the figure that with the increase in the amount of the collector, the Au grade in the coarse concentrate gradually decreased while the Au recovery gradually increased. With the increase in the amount of the collector, more gold minerals and gangue minerals entered the coarse concentrate, resulting in the recovery of Au in the coarse concentrate, which gradually increased, while the grade of Au gradually decreased. When the amount of the collector increased from 100 g/t to 300 g/t, the Au grade in the coarse concentrate gradually decreased from 30.28 g/t to 22.18 g/t, and the Au recovery gradually increased from 82.36% to 86.85%. The influence rule of the amount of collector on the coarse concentrate index was analyzed comprehensively, and the appropriate amount of the collector was determined to be 250 g/t.

3.2.6. Foaming Agent Dosage Condition Test

The fineness of grinding accounted for 85% of -0.074 mm; the dosage of sodium carbonate was 1000 g/t, the dosage of kerosene was 2000 g/t, the dosage of copper sulfate was 400 g/t (Fr 200 g/t, Sr 200 g/t), and the dosage of isoamyl xanthate was 250 g/t (Fr 125 g/t, Sr 125 g/t). The dosage of foaming agent 2# oil was 80 g/t (Fr 30 g/t, Sr 50 g/t), 100 g/t (50 g/t, 50 g/t), 120 g/t (70 g/t, 50 g/t), 140 g/t (90 g/t, 50 g/t), 160 g/t (110 g/t, 50 g/t), respectively. The influence law of the foaming agent dosage on the flotation index was investigated. The test process is shown in Figure 21, and the results are shown in Figure 22.

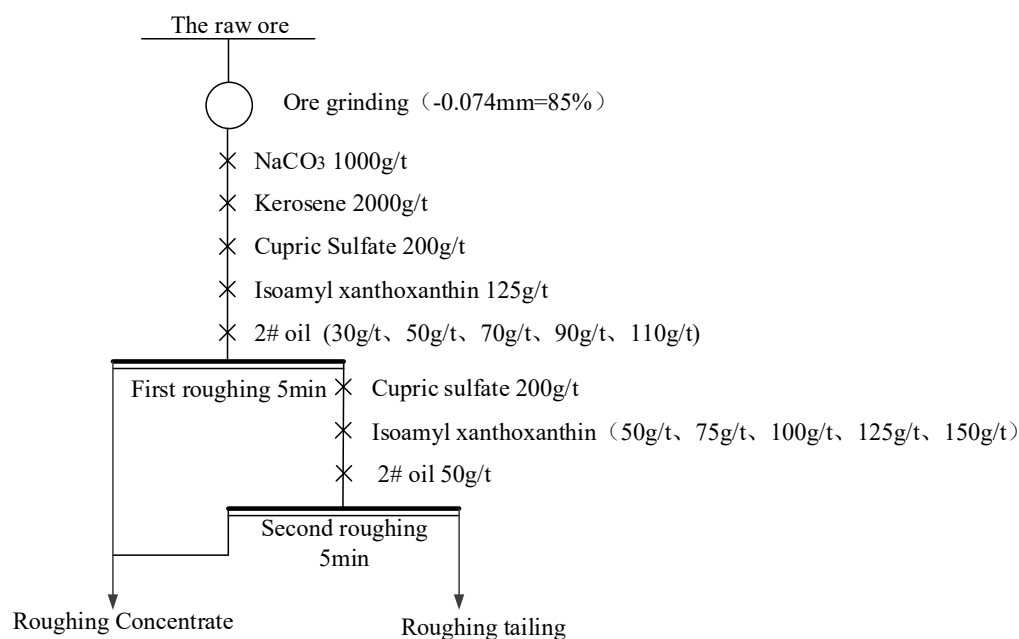


Figure 21. Foaming agent dosage condition test flow.

It can be seen from Figure 22 that with the increase in the dosage of the foaming agent, the Au grade in coarse concentrates showed a gradually decreasing trend, while the recovery rate showed a slowly increasing trend. When the dosage of the foaming agent increased from 80 g/t to 120 g/t, the recovery rate of Au increased from 84.52% to 87.89%. When the dosage of the foaming agent further increased to 160 g/t, the Au recovery tended to be flat and remained basically unchanged. When the dosage of the foaming agent increased from 80 g/t to 160 g/t, the Au grade in the coarse concentrate gradually decreased from 29.74 g/t to 26.60 g/t. The influence of the foaming agent dosage on the coarse concentrate index was analyzed comprehensively, and the appropriate foaming agent dosage was determined to be 120 g/t (70 g/t for primary crude and 50 g/t for secondary crude).

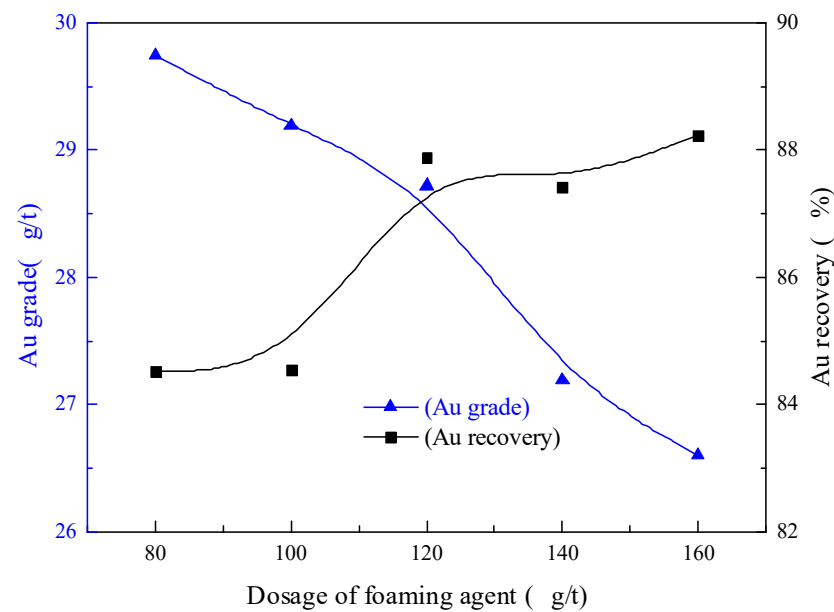


Figure 22. Influence of foaming agent dosage on Au separation index in concentrate.

3.3. The Closed-Circuit Flotation Test

Under the optimum flotation reagent system, the flotation closed-circuit test was carried out in order to obtain the ideal separation index. In order to further obtain the ideal index, this process was optimized on the basis of the conditional test, and one more selection was added. Finally, the closed-circuit flotation process of “two roughing, three cleaning and two scavenging” was adopted. The closed-circuit flotation test results are shown in Figure 23.

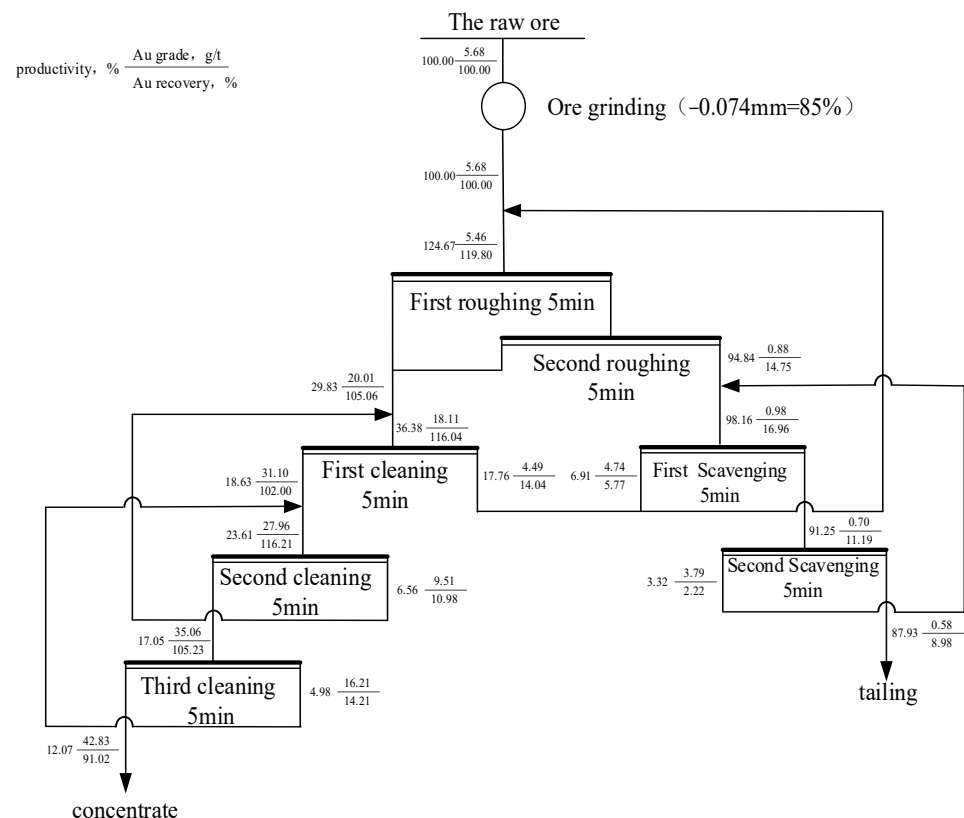


Figure 23. Flotation closed circuit process.

From the closed-circuit flow chart, we know that after the “two roughing, three cleaning and two scavenging” flotation closed-circuit process, the concentrate Au grade of 42.83 g/t and Au recovery rate of 91.02% could be obtained, reaching the technical target required by the contract. The final tailings contained 0.58 g/t Au, and the recovery rate of Au was 8.98%. The above test results show that the gold minerals in the ore effectively recovered. The flotation separation of gold and gangue minerals was realized.

3.4. Property Analysis of Flotation Concentrate and Tailings

Table 4 shows that the content of Au and Ag in the flotation concentrate was 42.83 g/t and 71.70 g/t, respectively. The contents of TFe and S were 24.47% and 29.70%, respectively. In addition, it also contained the elements of C and As, whose contents are 3.0% and 2.72%, respectively. The content of Au in the flotation tailing was only 0.58 g/t, the content of Ag was less than 1 g/t, and the contents of other metal elements, such as S, C, and As, were low. According to the results of concentrate and tailing data, it can be shown that the separation of gold-bearing minerals was effectively realized.

Table 4. Properties of flotation concentrate and tailing.

Elements	Au (g/t)	Ag (g/t)	TFe	S	C	As
Content/%	42.83	71.70	24.47	29.70	3.0	2.72
Elements	Au (g/t)	Ag (g/t)	TFe	S	C	As
Content/%	0.58	<1	2.62	0.117	0.797	0.031

Through the analysis of flotation concentrate and tailing properties from Table 4, we know that the grade and recovery rate of the gold concentrate are high and can meet the production requirements. This shows that when using kerosene as an auxiliary collector combined with xanthate flotation, the harmful impurities C and As had little impact on the flotation results. In fact, due to the addition of kerosene, it can effectively adhere to the surface of graphite or organic carbon, forming carbon–oil clusters. The cluster itself has a collector property for gold, forming carbon–oil–gold aggregates, thereby increasing the probability of gold-adhering bubbles, as shown in Figure 24 [35,36]. At the same time, this carbon–oil agglomeration can also reduce the amount of xanthate and avoid the adsorption of xanthate by graphite or organic carbon, thus reducing the collection effect [22,37]. However, this carbon–oil–gold cluster can enter the gold mining product together, and another part of the carbon and arsenic in the raw ore enters the concentrate, combined with mineralogy analysis; this is because another part of carbon is embedded in the sulfide ore and arsenopyrite, as a gold carrier, is difficult to be effectively separated via ordinary grinding and flotation [31,38]. Significantly, the C and As in the gold concentrate can have an impact on the subsequent gold-leaching treatment, causing a gold-robbing effect or reacting with the gold-leaching agent [9,39]. Therefore, for the gold concentrate containing carbon and arsenic, we removed the harmful elements such as C and As during pretreatment and then carried out leaching for gold extraction [40–42]. Since C and As are enriched in the concentrate, it can be seen from Figure 23 that the concentrate yield was 12.07%, which is greatly reduced compared with the raw ore concentrate. Hence, the direct treatment of gold concentrate can effectively reduce the energy consumption of pretreatment and the dosage of chemicals in the leaching process.

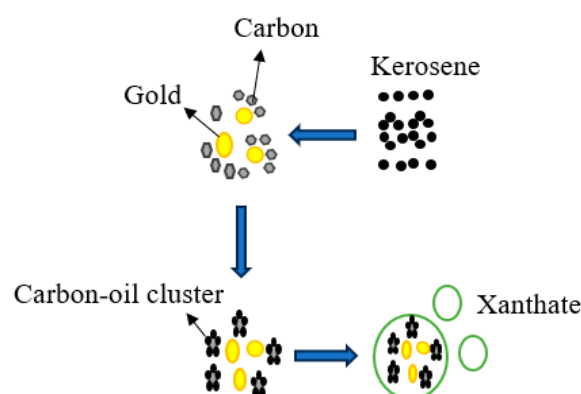


Figure 24. Carbon–oil cluster diagram.

4. Conclusions

In this paper, the mineral technology of the Fengcheng carbon–arsenic refractory gold ore was studied. According to the mineral characteristics, kerosene was used as the auxiliary collector, the best reagent system and technological process were determined, and the auxiliary mechanism and subsequent treatment were preliminarily analyzed according to the test products. The main conclusions are as follows:

- (1) The content of Au in the ore is 5.68 g/t, and the main minerals are quartz, muscovite, pyrite, and arsenopyrite, whose contents are 35.68%, 36.13%, 8.94%, and 1.05%, respectively. The gold ores are natural gold with a fine distribution and are mainly sulfide-coated gold, accounting for 79.46%. The main sulfide is pyrite, followed by arsenopyrite. The carbon content is 1.01%, and the main form is organic carbon.
- (2) The appropriate flotation process was determined as “two roughing, three cleaning and two scavenging”, and the reasonable grinding fineness were determined to be 85% of -0.074 mm. The flotation of the minerals was effectively separated using kerosene and collector flotation. The diversified utilization of kerosene was realized, which is of great significance for reducing mineral processing costs and ensuring environmental protection.
- (3) By using this experimental process, the concentrate with a Au grade of 42.83 g/t and recovery rate of 91.02% was obtained, and the contents of TFe and S were relatively high at 24.47% and 29.70%, respectively. In the final tailings, the Au grade was only 0.52 g/t, and the Ag content was <1 g/t; the TFe content was 2.62%. The contents of other metal elements, such as As, S, and C, were low.

In summary, the above test results show that kerosene as an auxiliary collector can effectively recover gold-bearing sulfide ore in refractory ores and realize the separation of gold and gangue. It is helpful in obtaining beneficiation costs, environmental protection, and the subsequent gold-leaching process.

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