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Study on mechanism of carbonaceous gold ore during oxidation roasting by kinetics: phase transformation and structure evolution

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Abstract

The pretreatment and effective utilization of carbonaceous gold ore is of significant to refractory gold resources. In this work, the calcination kinetics was employed to investigate the relationship between phase transformation and structure evolution of carbonaceous gold ore during roasting process. Mechanism functions were determined and the fact that roasting process was controlled by chemical reaction in the initial 90 min and dominated by internal diffusion as time reached to 120 min was uncovered. In addition, the apparent activation energies for initial and latter roasting stage were 212.11 kJ·mol⁻¹ and 163.73 kJ·mol⁻¹, respectively. Combined with the analysis of phase transformation and structure evolution, the removal of carbonaceous matter and appearance of new tiny pores contributed to the change of calcination kinetics. Moreover, phase transformation and structure evolution were beneficial for elevating Au recovery during leaching experiment. These findings helped to understand the mechanism of carbonaceous minerals during roasting and provided new insight for the utilization of refractory gold resource.

1. Introduction

With progressive exhaustion of non-refractory gold ores, refractory gold ores have become main materials for the production of gold, where 1/3 of gold in the world comes from [1, 2]. As a kind of refractory gold ore resources [3], deposit of carbonaceous gold ore account for more than 20% gold reserves over the world, containing more than 0.20% carbonaceous matter, Which deteriorate gold recovery through pre-robbing effect and the inhibition of gold by carbonaceous matter [4–6]. Therefore, the effective utilization has been concerned in the exploitation of gold ore and the problem in removal of carbonaceous matter is attracted extensive attention worldwide [7–9]. In order to eliminate the detrimental effect of carbonaceous matter for efficient recovery of gold, various methods have been proposed, such as oxidation roasting, bacterial oxidation, high pressure oxidation, and flotation [7, 10–12]. Particularly, oxidation roasting is used as one of the most popular pre-treatment techniques to remove carbonaceous matter [13–15]. In this way, carbonaceous matter will transfer to carbon dioxide (CO₂), thus the effect of ‘gold preg-robbing’ is eliminated [16, 17]. This technique not only promotes the recovery of gold, but also has the advantages of low pollution and simple operation to meet the expanded capacity requirement [18–20].

When the roasting temperature is higher than 500 °C, carbonaceous matter can be eliminated thoroughly and most gangue minerals (e.g., dolomite and calcite) can undergo thermal decomposition [21, 22]. As a result, large amounts of gas, such as, CO₂ and SO₂ are generated, which causes heat transfer resistances [23, 24]. On the other hand, the structure evolution is accompanied with phase transformation; this conjecture is strongly supported by our previous studies that the removal of carbonaceous matter and decomposition of gangue minerals produce new micropores [25]. The newly appeared pores can increase the specific surface area, total
pore volume and average pore size, which are beneficial for the oxygen circulation and heat transfer [26]. Therefore, it can be reasonably deduced that the phase transformation and structure evolution have significant effects on the calcination rate, which are supported by previous researches [27, 28]. However, seldom works are reported on the relationship between phase transformation and structure evolution in carbonaceous gold oxidation roasting process.

Calcination kinetics stands out as effective method to study chemical behaviors during oxidation roasting [29–31]. It was reported that the roasting of limestone conforms to the shrinkage core model and is controlled by surface chemical reactions, indicating that the mineral surface proprieties are the dominant factor during oxidation roasting process [32]. The roasting mechanism of nickeliferous silicate laterite ore was clarified by means of calcination kinetics, and obtained high grade concentrate containing 9.20% nickel with a nickel recovery of 88.80% [33]. Specifically, effects of the carbonaceous-matter on the phase and structure evolution of the coal-series kaolin during the calcination process were uncovered by means of kinetics. It was found that the scale-shaped lamellar structures samples became irregular and amorphous accompanied with the thermal decomposition of kaolin [34]. All mentioned works here proved the close connection between phase transformation and structure evolution.

Therefore, for better understanding of roasting mechanism of carbonaceous gold ore, calcination kinetics is employed to investigate the relationship between phase transformation and structure evolution during oxidation roasting carbonaceous gold ore. The calcination kinetics was quantified with models of chemical reaction, internal diffusion and external diffusion. Phase transformation during oxidation roasting was examined by XRD and TG-DSC. Structure evolution were identified by analysis on surface and pore structure. This work will provide new insight to the utilization of carbonaceous gold ore for providing theoretical foundation on the control the phase transformation and structure evolution during oxidation roasting.

2. Material and methods

2.1. Materials

The carbonaceous gold ore used in this study was obtained from Qinling Mountain, (Shaanxi Province, China). The chemical composition of the raw ore was presented in table 1. The proportions of Au, SiO₂ and total carbon (TC) in the carbonaceous gold raw ore samples were 5.20 × 10⁻⁶, 67.39% and 6.39%, respectively. X-ray diffraction patterns (XRD) were conducted to determine the phase composition of the raw ore as shown in figure 1. The results indicate that quartz, dolomite, calcite, sericite, kaolinite, pyrite and graphite are the major
crystallized minerals present in the raw ore. Particularly, the main gangue mineral is quartz, and the main carbonaceous matter is graphite.

### 2.2. Experiment of roasting and leaching

Schematic diagram of experimental setup of the gold roasting-leaching process is shown in figure 2. The procedure is described as follows.

The experiment of roasting was performed in rotary resistance-heated furnace (Model: HB-J-30, Xi’an, China) with different roasting temperature and time. Firstly, block materials were ground and screened to <2 mm samples. Then 500 g sample placed in crucible was roasted in furnace each time. Finally, these samples were taken out and cooled down to room temperature as roasting process finished. The samples were analyzed and weighted to calculate the gold grade and weight loss.

The leaching experiment was conducted in a 1.5 l leaching tank. Before the leaching operation, 100 g calcined products were ground for 5 min in a wet rod mill (Model: Φ160 mm × 240 mm, Wuhan, China), then leaching experiments were carried out at predetermined parameter that leaching time of 24 h, pH of 12, liquid-solid ratio of 3:1, NaCN dosage of 0.3%). Finally, leaching residue were collected by centrifugation and dried at 60 °C to measure the gold grade.

### 2.3. Samples characterization

The gold concentration was determined by atomic absorption spectrometry (TAS-990F, Beijing, China), and the leaching rate of gold was calculated according to equation (1):

$$\eta = \left(1 - \frac{\theta}{\beta}\right) \times 100\%$$  \hspace{1cm} (1)

where $\eta$ is the leaching rate of gold, (wt. %); $\theta$ is the gold grade of leaching residue, (g t$^{-1}$); $\beta$ is the gold grade of sample after roasting, (g t$^{-1}$).

The phase compositions of the samples were characterized by x-ray diffraction system manufactured by Bruker, German, operating at 40 kV and 30 mA with 2$\theta$ ranging from 5° to 80°. Comprehensive thermal analysis experiments were characterized under air-atmosphere at heating rates of 30 °C min$^{-1}$ from 25 °C to 900 °C by using the STA449c/3/G thermal analyzer (Netzsch Scientific Instruments Trading Ltd., SelbCity, Germany).

Pore structure analysis were measured by the surface area and porosity analyzer (ASAP 2020, Micromeritics, America). Adsorption/desorption isotherms of N$_2$ were acquired at −196 °C, after a pretreatment performed for 2 h at 200 °C under vacuum. The surface area and porosity were determined by using the BET equation and the Barret Joyner and Halenda (BJH) method respectively, and then theoretically the volume of the internal pores of the calcine was calculated.

The microstructures of samples were analyzed by using a Quanta 650 scanning electron microscope (FEI, Hillsboro, USA). SEM images were obtained at a high vacuum with an acceleration voltage of 30 kV and a working distance of 20 μm to 400 μm. Different magnifications (upto ×10000) were used for secondary electron images and an integration time of 50 s was employed to improve the signal-to-noise ratio.

### 2.4. Kinetic study

In this work, the roasting mechanism and kinetic parameters were analyzed by employing Coats–Redfern (CR) kinetic method, which is described as follows:
where \( g(\alpha) \) is an integral form of the kinetic function, \( \alpha \) is the extent of reaction, \( T \) is temperature of reaction, \( A \) is a pre-exponential factor, \( R \) is the gas constant, \( \beta \) is the heating rate and \( E_\alpha \) is activation energy. Linear regression analysis of above results was conducted according to the equation (2), the activation energy \( E_a \) and pre-exponential factors \( A \) were calculated from the slope and y-intercept.

3. Results and discussion

3.1. Effect of temperature on roasting process
The effect of temperature on roasting process was investigated at 500 °C, 550 °C, 600 °C, and 650 °C. As shown in figure 3, the weight loss changed about 5.20%, 6.00%, 7.02% and 8.01% at 500 °C, 550 °C, 600 °C and 650 °C after roasted for 120 min, respectively.

The results indicated that the weight loss increased with increasing temperature and time, especially the former one affected more significantly. Besides, the weight change increased direct linearly from 0 to 90 min, but displayed nonlinear variation from 90 min to 120 min. Therefore, it was considered that the oxidation roasting process of carbonaceous gold ore underwent different mechanisms with time.

3.2. Reaction mechanisms in roasting process
For better understanding of the mechanism during oxidation roasting process, calcination kinetics analysis was employed to define the chemical behaviors during thermal reactions [35–37]. Table 2 listed several common kinetic equations in oxidation roasting, such as external diffusion, internal diffusion, chemical reaction, decomposition reaction, decomposition reaction of two-dimensional diffusion and three-dimensional diffusion [38, 39]. The most probably kinetic models, in other words, the mathematical expression of \( g(\alpha) \) function was categorized by comparing the linear regression coefficient \( (R^2) \) of varied kinetic models [40]. The values of \( R^2 \) were obtained by calculating \( \alpha \) with different kinetic equations that unveiled diverse reaction mechanisms.

![Figure 3. Effects of temperature on weight loss during roasting process.](image-url)

### Table 2. Kinetic equations in oxidation roasting.

| Eqs | Equations: \( g(\alpha) = k(T)t \) | Reaction mechanisms |
|-----|----------------------------------|---------------------|
| \( F_1(\alpha) \) | \( \alpha = k_1t \) | External diffusion |
| \( F_2(\alpha) \) | \( 1 - (1-\alpha)^{\beta} + 2(1-\alpha) = k_2t \) | Internal diffusion |
| \( F_3(\alpha) \) | \( 1 - (1-\alpha)^{\beta} = k_3t \) | Chemical reaction |
| \( F_4(\alpha) \) | \( 2(1-\alpha)\left[-b(1-\alpha)^{\beta}\right] = k_4t \) | Decomposition reaction |
| \( F_5(\alpha) \) | \( \left[-b\ln(1-\alpha)\right]^{-\frac{1}{\beta}} = k_5t \) | Decomposition reaction (two-dimensional diffusion) |
| \( F_6(\alpha) \) | \( (1-\alpha)^{\beta}(1-\gamma)(1-\alpha)^{\gamma} = k_6t \) | Decomposition reaction (three-dimensional diffusion) |

\[
\ln \frac{g(\alpha)}{T^2} = \ln \left( \frac{AR}{\beta E_\alpha} \right) - \frac{E_\alpha}{RT} \tag{2}
\]

where \( g(\alpha) \) is an integral form of the kinetic function, \( \alpha \) is the extent of reaction, \( T \) is temperature of reaction, \( A \) is a pre-exponential factor, \( R \) is the gas constant, \( \beta \) is the heating rate and \( E_\alpha \) is activation energy. Linear regression analysis of above results was conducted according to the equation (2), the activation energy \( E_a \) and pre-exponential factors \( A \) were calculated from the slope and y-intercept.
mechanisms. According to $R^2$ obtained in fitting results, the mechanism function was finally determined when $R^2$ was closer to 1 \cite{41, 42}.

As discussed above, the oxidation roasting process of carbonaceous gold ore might undergo different mechanisms with time. Thus, a two-stage study of calcination kinetics was investigated from 0 to 90 min and 90 to 120 min. Fitting results were displayed in table 3, revealing that $R^2$ of $F_1(\alpha)$ at 500 °C, 550 °C, 600 °C and 650 °C were 0.9886, 0.9959, 0.9995 and 0.9938 in the first stage from 0 to 90 min respectively. Especially, $R^2$ in this group were closer to 1 than other calcination kinetic models, indicating that the roasting process was controlled by chemical reaction from 0 to 90 min. As time further extended to 120 min, $R^2$ of $F_2(\alpha)$ at 500 °C, 550 °C, 600 °C and 650 °C were 0.9981, 0.9837, 0.9935 and 0.9900 respectively, which were much more closer to 1 than other kinetic models. Therefore, the fact that roasting process was dominated by internal diffusion in the second stage from 90 min to 120 min was uncovered.

The simulated data of the most probably calcination kinetics at two stages (0 ~ 90 min and 90 ~ 120 min) were shown in figures 4(A) and (B). The apparent reaction rate constants $k$ were obtained by calculating slope of reaction models and listed in table 4. The apparent activation energy $E_a$ and pre-exponential factor $A$ were obtained according to equation (2), and the results were shown in figures 3(C), (D) and table 5. The results

| Time min $^{-1}$ | Temperature/°C | $F_1(\alpha)$ | $F_2(\alpha)$ | $F_3(\alpha)$ | $F_4(\alpha)$ | $F_5(\alpha)$ | $F_6(\alpha)$ |
|------------------|----------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 0 ~ 90           | 500            | 0.9861       | 0.8949       | 0.9886       | 0.9464       | 0.6116       | 0.6116       |
|                  | 550            | 0.9903       | 0.9245       | 0.9959       | 0.9648       | 0.6345       | 0.6345       |
|                  | 600            | 0.9795       | 0.9413       | 0.9995       | 0.9756       | 0.7114       | 0.7114       |
| 90 ~ 120         | 650            | 0.9723       | 0.9698       | 0.9938       | 0.9562       | 0.7078       | 0.7078       |
|                  | 500            | 0.8987       | 0.9981       | 0.9001       | 0.8690       | 0.7967       | 0.7967       |
|                  | 550            | 0.7857       | 0.9837       | 0.7872       | 0.7608       | 0.7093       | 0.7093       |
|                  | 600            | 0.8462       | 0.9935       | 0.8477       | 0.8228       | 0.7759       | 0.7759       |
|                  | 650            | 0.7990       | 0.9900       | 0.8004       | 0.7799       | 0.7451       | 0.7451       |

Note: The most probably mechanism was boded.
showed that $E_a$ and $A$ of calcination kinetics at initial stage were 212.11 kJ·mol$^{-1}$ and 157.83 min$^{-1}$, respectively. Parameters at latter stage were 163.73 kJ·mol$^{-1}$ and 9.93 min$^{-1}$, respectively.

The oxidation roasting process of carbonaceous gold ore was illustrated schematically in figure 5 based on kinetic analysis. In the gas-solid reaction model, assuming that the reactants are spherical particles with uniform particle size and surface chemical activity, and carbonaceous and gangue minerals coexist closely, and the volume of solid samples changes little during the oxidation process, the reaction kinetics of the roasting process can be treated according to the shrinkage unreacted core model. In this model, the chemical reaction is controlled by external diffusion, internal diffusion and chemical reaction. In the solid-solid reaction model, the surface of mineral particles is covered by new products during the reaction, and with the continuous progress of the reaction, the more the thickness of the product layer increases, the more seriously the oxygen diffusion is blocked. It is preliminarily concluded that the reaction process is controlled by the diffusion rate.

Within the roasting time range of 0–120 min (figure 3), the oxidation roasting process of carbonaceous gold ore can be divided into two stages: 0–90 min and 90–120 min according to the weight loss of the calcine. The best kinetic mechanism function of carbonaceous gold ore during roasting time of 0–90 min is $f(\alpha) = 1 - (1 - \alpha)^{1/3}$, that is, the roasting process is mainly controlled by gas-solid chemical reaction. Due to the large contact area between oxygen in the air and particles, pyrite, graphite and kaolinite in the particles undergo oxidation or decomposition reaction, and the reaction is gradually promoted to the inside of the particles. In the process of 90–120 min, the best kinetic mechanism function is $f(\alpha) = 1 - 3(1 - \alpha)^{2/3} + 2(1 - \alpha)$, which shows that this stage is mainly controlled by gas-solid internal diffusion reaction. The process is that the reactants diffuse from the outside to the inside of the particles, and the products diffuse from the inner surface to the outer surface. It is worth noting that the chemical reaction rate of this process is slow. The mechanism function of carbonaceous gold ore is different in the roasting process of 0–90 min and 90–120 min, indicating that the control mechanism is changing with the roasting process.

![Figure 5. Schematic diagram of oxidation roasting process based on kinetic analysis.](image)

| Temperature/$°$C | 0 ~ 90 min | 90 ~ 120 min |
|-----------------|-------------|--------------|
| 500             | $1.21 \times 10^{-4}$ | $1.92 \times 10^{-5}$ |
| 550             | $1.50 \times 10^{-4}$ | $2.30 \times 10^{-5}$ |
| 600             | $1.88 \times 10^{-4}$ | $2.78 \times 10^{-5}$ |
| 650             | $2.30 \times 10^{-4}$ | $3.13 \times 10^{-5}$ |

| Roasting time   | Reduction rate equations | Kinetic models $E_a$/kJ·mol$^{-1}$ | $A$/min$^{-1}$ |
|-----------------|--------------------------|-------------------------------------|---------------|
| 0 ~ 90 min      | $f(\alpha) = 1 - (1 - \alpha)^{1/3}$ | Chemical reaction | 212.11        | 157.83        |
| 90 ~ 120 min    | $f(\alpha) = 1 - 3(1 - \alpha)^{2/3} + 2(1 - \alpha)$ | Internal diffusion | 163.73        | 9.93          |
3.3. Phase transformation

3.3.1. TG-DSC characterization

To explore the weight loss and exothermic behavior during the roasting process, TG-DSC analysis was conducted and result was shown in figure 6. The weight loss was about 1.49% from 100 °C to 371.32 °C, which was attributed to the loss of water after decomposition of kaolinite, as described in equation (3) [43]. The 0.92% weight loss from 371.32 °C to 461.39 °C was due to the oxidation of pyrite, which can be expressed as equation (4) [44]. Besides, 14.61% weight loss of is observed from 500 °C to 770 °C, which was due to the oxidation of graphite as described in equation (5) [26]. With the increasing of roasting temperature, the weight decreased 2.03% as temperature raised from 770 °C to 850 °C, which was caused by the CO₂ elimination after calcite decomposition as displayed in equation (6) [45]:

\[
\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} = \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 + 2\text{H}_2\text{O} \quad (3) \\
4\text{FeS}_2 + 11\text{O}_2 = 2\text{Fe}_2\text{O}_3 + 8\text{ SO}_2 \uparrow \quad (4) \\
\text{C} + \text{ O}_2 = \text{ CO}_2 \uparrow \quad (5) \\
\text{CaCO}_3 = \text{ CaO} + \text{ CO}_2 \uparrow \quad (6)
\]

3.3.2. XRD analysis

To explore the phase transformation of carbonaceous gold ore during oxidation roasting at 650 °C, XRD analysis was conducted at different roasting time as shown in figure 7. Diffraction peaks corresponding to sericite and kaolinite disappeared after roasting over 90 min [25]. Peaks at 25° and 28.3° corresponding to kaolinite and...
calcite and peaks of calcite at 41° and 45° weakened as roasting time extended to 90 min. Especially, figure 7(B) shows that the peak located at 26.78° disappeared, which is corresponding to graphite [46]. All changes mentioned above indicated that phase transformation occurred in minerals of sericite, kaolinite, graphite and calcite after 90 min oxidation roasting, which is consistent with the results of TG-DSC. However, no obvious change of characteristic peaks was detected during the period of time from 90 min to 120 min, revealing that no significant phase transformation occurred in this condition. All these detail information discussed confirmed that the roasting process was dominated by chemical reaction in the stage of 0 ~ 90 min.

3.4. Structure evolution

3.4.1. Pore structure analysis

To identify the pore structure evolution of carbonaceous gold ore during oxidation roasting, the adsorption-desorption isotherms and pore size distribution of samples for different roasting times were analyzed. Figures 8(A) and (B) showed that adsorption and desorption isotherms were not identical, where an obvious hysteresis loop appeared, indicating that isotherms of raw ore and sample roasted for 90 min were categorized as type IV with H3 hysteresis loops [47]. However, adsorption-desorption isotherm in figure 8(C) coincided completely in Y-axis, suggesting the isotherm of sample roasted for 120 min were identified as type III with H3 hysteresis loops [48]. It revealed that pore structure of raw ore and samples roasted for 90 min was narrow and random-shaped, while there were circular and regular pores in samples that roasted for 120 min. In addition, as shown in figures 8(D)–(F), pore sizes of raw ore and samples roasted for 90 min were widely distributed less than 2 nm, while pore size ranged from 2 nm to 10 nm in samples roasted for 120 min. It proved that sufficient roasting time was beneficial for the growth of pore size, which was also emphasized in table 6 that the average pore size was 20.04 nm with the increase of roasting time to 120 min. Besides, the specific surface area and total pore volume were also the highest at 120 min. Moreover, the specific surface area and total pore volume share similar trends with the increase of average pore size. The result suggested no obvious pore structure evolution was observed during oxidation roasting form 0 to 90 min, but significant changes occurred as time extended to 120 min.

The increase of pore number in the calcine is beneficial to the whole roasting leaching process. On the one hand, it can promote the outside reactant air and heat to the inside of the particles, which is conducive to the

| Samples  | $S_{BET} (m^2 g^{-1})$ | $V_p (cm^3 \times 10^{-3} g^{-1})$ | $d_p (nm)$ |
|----------|------------------------|-------------------------------|----------|
| Unroasted| 2.05                   | 9.47                          | 18.02    |
| 90 min   | 2.19                   | 11.78                         | 18.69    |
| 120 min  | 3.09                   | 19.95                         | 20.04    |

Figure 8. Nitrogen adsorption-desorption isotherm and pore diameter distribution of samples at 650 °C for raw ore (A) and (D); roasted for 90 min (B) and (E); roasted for 120 min (C) and (F).

Table 6. Pore parameters of samples at 650 °C.
reaction of carbonaceous substances and other minerals. On the other hand, the products inside the particles can be discharged more timely. In addition, in the subsequent gold leaching process, it is conducive to the reaction of leaching agent with gold in the particle and improves the gold leaching rate. On the whole, the increase of the number and diameter of pores is conducive to material circulation and heat transfer.

3.4.2. Morphology structure

The microstructure evolution of samples during roasting process was studied by SEM as displayed in figures 9(A) and (B). SEM images revealed that the surface of unroasted sample was regularly and smoothly, but there were more pores and cracks on the surface of samples roasted for 90 min, proving that structural change in this period of time. Furthermore, porous structure with large pores appeared when time further reached to 120 min, demonstrating that a significant structure evolution happened form 90 min to 120 min as displayed in figure 9(C). The zones marked in figures 9(A)–(C) was analyzed by EDS and the results were listed in next to SEM images. Obviously, C element was observed in the marked position of unroasted sample shown in figure 9(A).
None of C element was found in the marked position of roasted samples shown in figures 9(B) and (C), indicating that carbonaceous substance had completely oxidized or decomposed. On the basis of TG-DSC and XRD analysis, it was considered that escape of CO₂ produced by oxidation of carbonaceous matter and decomposition of calcite, was responsible for the microstructure evolution, where new produced tiny pores were beneficial for the heat transfer during the oxidation roasting [24]. Combined with the results of kinetic analysis, the roasting process was dominated by internal diffusion from 90 min to 120 min, which was attributing to the structure evolution.

3.5. Effect of oxidation roasting on gold recovery

Ultimately, the effect of oxidation roasting on gold leaching recovery was investigated as illustrated in figure 10. It showed that the Au recovery was only 12.57% for the raw ore without pretreatment. When the roasting temperature was 500 °C, 550 °C, 600 °C, 650 °C, the Au recovery was promoted to 85.24%, 87.65%, 90.45% and 91.28% after roasting for 120 min, respectively. According to the result in figure 6, Au recovery shared similar trend with the weight loss during oxidation roasting, indicating that phase transformation and structure evolution both influenced Au recovery significantly during leaching process.

On the basis of above analysis, the mechanism of the effect of phase transformation and structure evolution on gold recovery was proposed. During the early stage of oxidation roasting from 0 to 90 min, the ‘gold preg-robbing’ effect was mitigated with the content of graphite substantially decreases in samples to promote the recovery of Au. On the other hand, during the latter stage of 90 °C ∼ 120 min, the structure evolution was responsible for the increase of Au recovery. Due to the formation of these new tiny pores, the refractory Au has been exposed. Therefore, the phase transformation and structure evolution during oxidation roasting was beneficial for gold recovery.

4. Conclusions

In this work, the calcination kinetic was employed to investigated the phase transformation and structure evolution of carbonaceous gold ore during oxidation roasting, the following conclusions can be drawn from this study:

The results of calcination kinetics revealed that the roasting process of carbonaceous gold ore could be divided into two stages. In initial stage form 0 to 90 min, the roasting process was controlled by chemical reaction and the expression of mechanism function was \( F(\alpha) = 1 - (1 - \alpha)^{2/3} \), and the activation energy was 88.89 kJ·mol\(^{-1}\). In the latter stage of 90 °C ∼ 120 min, internal diffusion was the dominant factor. The expression of mechanism function was \( F(\alpha) = 1 - 3(1 - \alpha)^{2/3} + 2(1 - \alpha) \) and the activation energy was 20.58 kJ·mol\(^{-1}\).

On the basis of kinetic results, analysis of phase transformation and structure evolution were employed to further investigate the mechanism of carbonaceous gold ore during oxidation roasting. During the initial stage in 90 min, the phase transformation, especially the oxidation of graphite, was controlled by chemical reaction. As time extended over 90 min to 120 min, more pores were generated on the surface and interior, thus the
internal diffusion dominant the roasting process. In addition, the removal of graphite and the increase of specific surface area, total pore volume and average pore size both are beneficial for improving the Au recovery.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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