Reaction mechanisms of low-grade molybdenum concentrate during calcification roasting process

Min GAN, Xiao-hui FAN, Xu-ling CHEN, Cheng-qian WU, Zhi-yun JI,
Song-rong WANG, Guo-jing WANG, Guan-zhou QIU, Tao JIANG
School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China

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Abstract: The effects of Ca-based additives on roasting properties of low-grade molybdenum concentrate were studied. The results show that calcium-based additives can react with molybdenum concentrate to form CaSO₄ and CaMoO₄. The initial oxidation temperature of MoS₂ is 450 °C, while the formation of CaMoO₄ and CaSO₄ occurs above 500 °C. The whole calcification reactions are nearly completed between 600 and 650 °C. However, raising the temperature further helps for the formation of CaMoO₄ but is disadvantageous to sulfur fixing rate and molybdenum retention rate. Calcification efficiency of Ca-based additives follows the order: Ca(OH)₂→CaO→CaCO₃. With increasing the dosage of Ca(OH)₂, the molybdenum retention rate and sulfur-fixing rate rise, but excessive dosages would consume more acid during leaching process. The appropriate mass ratio of Ca(OH)₂ to molybdenum concentrate is 1:1. When roasted at 650 °C for 90 min, the molybdenum retention rate and the sulfur-fixing rate of low-grade molybdenum concentrate reach 100% and 92.92%, respectively, and the dissolution rate of molybdenum achieves 99.12% with calcines being leached by sulphuric acid.

Key words: molybdenum concentrate; calcification roasting; reaction mechanism; thermodynamic analysis; phase transformation

1 Introduction

Molybdenum concentrate is commonly extracted after MoS₂ is oxidized to high-valence molybdenum [1]. Two kinds of oxygenolysis processes for molybdenum concentrates are usually applied. One is pyrometallurgy, the other refers to hydrometallurgy which has been developed since 1970s [2]. Pyrometallurgy includes the process of oxidizing roasting, alkali fusing method and additive roasting [3]. In China, oxidizing roasting process is the most widely applied process, which commonly roasts molybdenum concentrates in rotary kiln, multiple hearth furnace, flash furnace etc. However, for low-grade molybdenum concentrate with abundant impurities such as calcium, magnesium, copper, iron and lead, low-melting-point compounds can easily be generated during oxidation roasting, which will lead to agglomeration and even restrict the thorough oxidation of MoS₂. Meanwhile, molybdates that are indissolvable in ammonia and further impede the recovery of molybdenum are easy to form. In addition, the low SO₂ concentration in roasting flue gas makes its recovery costly and causes environmental pollution [4]. Hydrometallurgical processing refers to oxygen pressure process [5–7], nitric acid decomposition [8,9], sodium hypochlorite oxidation [10,11], electro-oxidation [12,13] and bioleaching method [14,15]. Although hydrometallurgy has the advantage of solving SO₂ emission problem, lacking low-cost oxidant makes it difficult to solve the problem thoroughly. Meanwhile, some impurities like metal compounds are easy to dissolve, which increases the difficulties of the follow-up purification. As a result, the high cost of leaching and purification restricts the development of hydrometallurgy to process low-grade molybdenum concentrates mostly [16,17].

Consequently, the key point of low-grade molybdenum concentrate utilization lies in improving the oxidation efficiency of molybdenum and resolving SO₂ pollution problem. Benefiting from the effects of calcium-based additives during roasting, calcification
roasting is able to fix sulfur and inhibit the volatilization of MoO$_3$ together with SO$_2$, and the generated CaMoO$_4$ can be fully dissolved in acid. This method is prospective to solve current problems in oxidizing roasting and hydrometallurgical processing. So, the selection of additives for calcification roasting was investigated in this work, and the mechanisms of sulfur fixing and MoS$_2$ oxidization during calcification roasting were revealed, based on which a novel method for effectively handling low-grade molybdenum concentrate was provided.

2 Experimental

2.1 Materials

The chemical composition of molybdenum concentrate is shown in Table 1. The molybdenum content is 39.27%, which is lower than that of standard-molybdenum concentrate with Mo content above 45%. The impurity substances mainly consist of SiO$_2$, CaO, MgO, and iron-containing minerals. According to the mineral compositions of molybdenum concentrate (Table 2), the major component is molybdenite, which takes up 65.4%, followed by sulfide ores including copper pyrites, bornite and iron pyrite. There are also iron oxides mainly consisting of limonite and hematite, silicon gangue minerals composed of aluminosilicate, magnesium-silicate and quartz, and carbonates composed of calcite and dolomite.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mass fraction (%)</th>
<th>Mineral</th>
<th>Mass fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenite</td>
<td>65.4</td>
<td>Iron oxides</td>
<td>4.2</td>
</tr>
<tr>
<td>Copper pyrites and bornite</td>
<td>2.4</td>
<td>Aluminosilicate (mica, feldspar)</td>
<td>3.7</td>
</tr>
<tr>
<td>Pyrite</td>
<td>8.0</td>
<td>Magnesium-silicate (chlorite, talc)</td>
<td>3.1</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>0.02</td>
<td>Carbonate (calcite, dolomite)</td>
<td>8.4</td>
</tr>
<tr>
<td>Galena</td>
<td>0.02</td>
<td>Quartz</td>
<td>3.7</td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>0.02</td>
<td>Others</td>
<td>1.04</td>
</tr>
</tbody>
</table>

The mineral dissemination characteristics of molybdenum concentrate are investigated by optical microscope, as can be seen in Fig. 1. Molybdenite mainly appears as monomer particle with sizes of 0.02–0.20 mm, which are scale-like, slab-like, strip and irregular particles. Few molybdenite particles are interlocked by pyrites otherwise coated by large particles of copper pyrites, which indicates that molybdenite and other sulfide ores are embedded closely. Most of calcite, quartz and silicate have been dissociated from molybdenite.
equipments such as X-ray diffraction (XRD) and scanning electronic microscope (SEM). XRD measurements were performed on the samples with a powder diffractometer (Rigaku D/M4X 2500) using a Cu Kα radiation. The range of scanning angle (2θ) was from 5° to 100° and the scanning speed was 0.2156 (°)/s. SEM (JEOL JSM−5600) with energy dispersive X-ray (EDX) was used to analyze particle morphology and major chemical distribution in typical minerals.

**Fig. 2** Flow diagram of calcification roasting−acid leaching

Roasted products were ground into 0.074 mm with mass fraction above 80%, and then samples were obtained for examining the contents of molybdenum and sulfur. Another 5 g calcine was added into flasks containing dilute sulfuric acid for leaching molybdenum. The acid leaching conditions were set up as follows: sulfuric acid concentration of 70 g/L, temperature of 90 °C, time of 2 h, and liquid−solid ratio of 5:1. After leaching, the suspended solution was filtrated using a vacuum filter, and then the content of molybdenum in the residue was analyzed.

The evaluation indicators of roasting−acid leaching process mainly contain the leaching rate of molybdenum (αMo), the retention rate of molybdenum (ηMo) and the sulfur-fixing rate βs, which can be calculated as follows:

\[ \alpha_{Mo} = \frac{m_2 w_2 - m_1 w_3}{m_2 w_2} \times 100\% \]  
\[ \eta_{Mo} = \frac{m_2 w_2}{m_1 w_1} \times 100\% \]  
\[ \beta_s = \frac{m_2 w_5}{m_1 w_4} \times 100\% \]

where \( m_1 \), \( m_2 \) and \( m_3 \) stand for the mass of molybenite concentrate, molybdenum calcine and leaching residue, respectively; \( g; w_1, w_2 \) and \( w_3 \) stand for the mass fractions of molybdenum in molybenite concentrate, molybdenum calcine and leaching residue, respectively, \( \% \); \( w_4 \) and \( w_5 \) stand for the mass fractions of sulfur in molybenite concentrate and molybdenum calcine, respectively, \( \% \).

3 Results and discussion

3.1 Thermodynamics of calcification roasting process

During the roasting process of molybdenum concentrate, the reactions of MoS₂ oxidation, calcium molybdate generation and sulfur-fixing reaction occur potentially. And the oxidation of MoS₂ is shown as:

\[ \frac{2}{7} \text{MoS}_2 + \frac{1}{7} \text{O}_2(g) = \frac{2}{7} \text{MoO}_3 + \frac{4}{7} \text{SO}_2(g) \]

\[ \Delta G^\theta_{T} = -300.83 + 0.05T \text{ (kJ/mol)} \]

When the temperature is lower than 6000 K, MoS₂ oxidation reaction is spontaneous because of \( \Delta G^\theta_{T} < 0 \). As calcium-based additives were mixed with molybdenum concentrate, calcium-based additives can react with the oxidative products of MoS₂ like MoO₃ and SO₂. The thermodynamic conditions of the formation reactions of molybdate and the sulfation reactions are shown in Fig. 3. If the temperature is below 798 K, the easy tendencies of different calcium-based additives reacting with MoO₃ and SO₂ to generate CaMoO₄ and CaSO₄ can be ranked as CaO>Ca(OH)₂>CaCO₃. While at the temperature of
above 798 K, the order changes to be $\text{Ca(OH}_2\text{)>CaO>CaCO}_3$. As can be observed from the thermodynamic curves, CaO, MgO, FeO and CuO react with SO$_2$ below 1150 K, and the products are CaSO$_4$, MgSO$_4$, FeSO$_4$ and CuSO$_4$, respectively. However, the reaction tendency decreases successively. CuSO$_4$ is resolved into CuO and SO$_2$ above 1150 K, and FeSO$_4$ will be decomposed above 1300 K. But CaSO$_4$ and MgSO$_4$ are only decomposed at high temperatures, which proves that sulfur-fixing reactions are qualified to proceed during the calcification roasting process.

Although there are differences in reactive ability of three calcium-based additives, the formation of molybdate and the sulfation reaction occur spontaneously in the temperature range of 400–1300 K. Therefore, the oxidation and calcification reactions are carried out simultaneously according to thermodynamic analysis.

### 3.2 Effects of calcium-based additives on roasting

As adding calcium-based additives with their theoretical quantities (theoretical amount means that molybdenum and sulfur convert to CaMoO$_4$ and CaSO$_4$ completely, and theoretical amounts of CaO, Ca(OH)$_2$ and CaCO$_3$ are the mass ratios of 0.64:1, 0.84:1 and 1.13:1 compared with molybdenum concentrate), the effects of roasting temperature on the roasting–leaching process of molybdenum concentrate at the roasting time of 90 min are given in Fig. 4. With temperature rising, the retention rate of molybdenum decreases gradually. Especially when the temperature increases to above 750 °C, the retention rate of molybdenum is observed to decrease apparently. The reason is that MoS$_2$ is oxidized to MoO$_3$ rapidly and part of MoO$_3$ volatilized before reacting with calcium-based additives at high temperatures. The loss of molybdenum is relatively small below 700 °C. Using Ca(OH)$_2$ achieves the highest retention rate of molybdenum, which nearly reaches 100% at 650 °C. Differences in the sulfur-fixing rate of these additives are studied, adsorption efficiency firstly increases and then decreases with the temperature rising. According to its effects, the sulfur-fixing rate of different additives can be ranked as Ca(OH)$_2$>CaO>CaCO$_3$, and the sulfur-fixing rate achieves the maximum at 650–700 °C. However, the sulfur-fixing rate is lower when using theoretic dosage of additives. During the experiments of leaching molybdenite by acid, the leaching rate increases with the rise of roasting temperature, but then the leaching rate increases at a slower pace above 700 °C. Taking the effects of three additives on retention rate of molybdenum, sulfur-fixing rate and leaching rate of molybdenum into consideration, 650 °C is suitable for roasting.

![Fig. 4](image) Effects of roasting temperature on calcification roasting and acid leaching

Figure 4 shows that the sulfur-fixing rate stays at a low level when using the theoretic dosage of additives, thus it is necessary to add more additives. When roasting molybdenum concentrate at 650 °C for 90 min, the effects of different additives on roasting–leaching rate are studied, and the results are shown in Table 3. On one hand, with increasing the dosage of Ca(OH)$_2$ or CaO, the retention rate and the leaching rate of molybdenum and the sulfur-fixing rate tend to increase; on the other hand, increasing the dosage of CaCO$_3$ improves both the retention rate of molybdenum and the sulfur-fixing rate, while the leaching rate of molybdenum increases firstly and then decreases for the reason that excessive CaCO$_3$ consumes more acid, which leads to lower leaching rate of molybdenum.

According to the retention rates and the leaching
rates of molybdenum, it can be concluded that all of the calcium-based additives can react with MoO$_3$ to generate CaMoO$_4$, and the reaction ability can be ranked as Ca(OH)$_2$ > CaO > CaCO$_3$. From the sulfur-fixing rate, it is believed that the sulfur-fixing efficiencies of Ca(OH)$_2$ and CaO are better than that of CaCO$_3$, and the sulfur-fixing efficiencies of Ca(OH)$_2$ are better than that of CaO. The sulfur-fixing rate with the addition of CaCO$_3$ is only 41.67% even though the dosage of CaCO$_3$ is 1.4 times of molybdenum concentrate, which indicates that the sulfur-fixing efficiency of CaCO$_3$ is inferior to that of other additives. When the mass ratio of Ca(OH)$_2$ to MoO$_3$ is 1:1, the retention rate of molybdenum reaches 100%, the sulfur-fixing rate attains 92.92%, and the leaching rate of molybdenum is 99.12%.

### Table 3 Effects of dosages of calcium-based additives on calcification roasting and acid leaching

<table>
<thead>
<tr>
<th>Additive</th>
<th>Mass ratio of additive to molybdenum concentrate</th>
<th>Retention rate of molybdenum/%</th>
<th>Sulfur-fixing rate/%</th>
<th>Leaching rate of molybdenum/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>0.60:1</td>
<td>98.61</td>
<td>54.73</td>
<td>89.09</td>
</tr>
<tr>
<td></td>
<td>0.64:1*</td>
<td>98.76</td>
<td>56.67</td>
<td>92.63</td>
</tr>
<tr>
<td></td>
<td>0.80:1</td>
<td>99.89</td>
<td>68.15</td>
<td>93.54</td>
</tr>
<tr>
<td></td>
<td>1.00:1</td>
<td>100.00</td>
<td>88.48</td>
<td>95.3</td>
</tr>
<tr>
<td>Ca(OH)$_2$</td>
<td>0.80:1</td>
<td>98.97</td>
<td>86.17</td>
<td>89.32</td>
</tr>
<tr>
<td></td>
<td>0.84:1*</td>
<td>99.99</td>
<td>87.90</td>
<td>95.58</td>
</tr>
<tr>
<td></td>
<td>1.00:1</td>
<td>100.00</td>
<td>91.49</td>
<td>99.12</td>
</tr>
<tr>
<td></td>
<td>1.20:1</td>
<td>100.00</td>
<td>93.57</td>
<td>99.18</td>
</tr>
<tr>
<td>CaCO$_3$</td>
<td>1.00:1</td>
<td>96.09</td>
<td>34.89</td>
<td>80.98</td>
</tr>
<tr>
<td></td>
<td>1.13:1*</td>
<td>96.25</td>
<td>36.50</td>
<td>85.11</td>
</tr>
<tr>
<td></td>
<td>1.20:1</td>
<td>97.14</td>
<td>37.99</td>
<td>71.20</td>
</tr>
<tr>
<td></td>
<td>1.40:1</td>
<td>97.38</td>
<td>41.67</td>
<td>52.16</td>
</tr>
</tbody>
</table>

* Theoretical values for molybdenum transforming to calcium molybdate

### 3.3 Phase evolution during calcification roasting process

In order to study the effects of additives on the particle morphology of calcine and the formation of products, energy dispersive X-ray spectrometric microanalyzer (EDS) with SEM is employed and the scanning pictures are shown in Fig. 5. In this study, the roasting process of molybdenum concentrate is performed under conditions of adding additives at theoretic ratios and roasting at 650 °C for 90 min. With the addition of CaCO$_3$, the original particle morphology is not changed after roasting, but some new phases appear on the surface and a few particles bond mildly. With the addition of CaO, crystalline transformation is observed mainly to be needle-like and granular, and other morphology of the complex interwoven structure is formed after sintering. With the addition of Ca(OH)$_2$, two kinds of particles with different crystalline forms appear, one is developed from aggregated particles, and the other is small monomer bean shaped particles.

![SEM images of roasted products with different calcium-based additives](image)

For revealing the types of products after roasting, the energy spectrum analyses of different zones in the calcine are applied, and the results are shown in Fig. 6. With the addition of Ca(OH)$_2$, well-crystallized CaSO$_4$ and CaMoO$_4$ appear in Zones A and B in (Fig. 6(a)). With the addition of CaO, the sulfur-fixing rate is evaluated to be lower. According to the analyses of
Fig. 6 SEM–EDAX patterns of different zones in Fig. 5 in calcine: (a) Zone A; (b) Zone B; (c) Zone C; (d) Zone D; (e) Zone E; (f) Zone F

Zones C and D in Fig. 5(b), the main component is CaMoO$_4$ and there are still a few of CaSO$_4$ and CaO. With the addition of CaCO$_3$, CaSO$_4$ and CaMoO$_4$ in roasted product are detected in Zones E and F, whose content of CaSO$_4$ is less than that with the addition of CaO. Illustrated by the results of SEM, reactions run smoothly and well-crystallized particles of CaMoO$_4$ and CaSO$_4$ are formed with the addition of Ca(OH)$_2$. In addition, the generation of CaMoO$_4$ becomes relatively difficult and the sulfur-fixing rate decreases obviously during the roasting process with the addition of CaCO$_3$ or CaO.

The roasted products, which come from the molybdenum concentrate that is roasted at 650 °C for 90 min with theoretic quantities of additives, are investigated by means of XRD and the patterns are shown in Fig. 7, from which it can be seen that the common phases of the calcines are CaMoO$_4$, CaSO$_4$ and Mg$_3$(Si$_4$O$_{10}$)(OH)$_2$. The intensities of the CaSO$_4$ diffraction peaks with different additives can be ranked...
as Ca(OH)$_2$>CaO>CaCO$_3$, which indicates that calcium-based additives are convinced to have the function on sulfur fixation. This agrees with the thermodynamic results.

The retention rates of molybdenum are 98.76%, 99.99% and 96.25% with the addition of CaO, Ca(OH)$_2$ and CaCO$_3$, respectively (Table 3). High retention rate of molybdenum indicates that the solid–solid reactions or gas–solid reactions between MoO$_3$ or MoO$_3$ (g) and additives can run smoothly. The sulfur-fixing rates being 56.67%, 87.90% and 36.50% respectively indicate that reactions between Ca(OH)$_2$ and SO$_2$ are able to proceed more sufficiently. The leaching rates of Mo in calcine are 92.63%, 95.58% and 85.11%, respectively. The phase analyses also sustain the fact that a large amount of calcium molybdate, which can be dissolved in acid, generates under the roasting temperature. Therefore, the most suitable calcium-based additive is Ca(OH)$_2$.

Ca(OH)$_2$ is the product of CaO hydration. Ca(OH)$_2$ colloid particles are formed in the process of hydration, which makes larger specific surface area of Ca(OH)$_2$ than that of CaO. Therefore, reactions are easily to proceed on the kinetics because of the larger contact area with molybdenum concentrate. Whereas, compared with CaCO$_3$, thermodynamics trend of reaction between Ca(OH)$_2$ and MoO$_3$, SO$_2$ is larger. Moreover, the decomposition temperature of CaCO$_3$ is high, it starts to decompose at 530 °C and decompose acutely at 900 °C to form CaO. As a consequence, the calcification efficiency of adding Ca(OH)$_2$ to roast molybdenum concentrate is the best.

Molybdenum concentrates with equivalent mass of Ca(OH)$_2$ are roasted for 90 min at different temperatures, the phase compositions of the products are analyzed, and the patterns are shown in Fig. 8.

The molybdenum phase is mainly composed of MoS$_2$ at about 400 °C, where the oxidation reaction does not start yet. When the temperature increases to 450 °C, the product of MoO$_3$ appears through the oxidization of MoS$_2$, and Ca(OH)$_2$ begins to decompose where the diffraction peak of CaO appears. The height diffraction peaks of MoS$_2$ and MoO$_3$ drop significantly while the diffraction peaks of CaMoO$_4$ and CaSO$_4$ appear at 500 °C. It can be known that MoO$_3$ and SO$_2$, which derive from the oxidization of MoS$_2$, begin to react with CaO. When the temperature is above 600 °C, the main diffraction peaks are those of CaMoO$_4$ and CaSO$_4$, and MoS$_2$ is completely transformed into CaMoO$_4$. The reaction process between molybdenum concentrate and Ca(OH)$_2$ is further proved by thermal gravity analysis. According to the TG–DSC curves (Fig. 9), the evaporation of moisture and the volatilization of something volatile go on before 400 °C. When the temperature ranges from 400 to 470 °C, the oxidization of sulfide and the decomposition of Ca(OH)$_2$ occur. When the temperature surpasses 470 °C, three exothermic peaks appear at 530.5, 574.4 and 640.9 °C, respectively, where the reaction speed of MoO$_3$
oxidation and the generation speed of CaMoO₄ and CaSO₄ are the fastest. As it has been introduced in Figs. 8 and 9, the transformation process is as follows: Ca(OH)₂ decomposition→MoS₂ oxidation→molybdate and sulfate generation.

3.4 Calcification roasting–acid leaching process

The quality flow chart of calcium-based roasting and acid-leaching process is shown in Fig. 10. According to the analysis of the calcine and the leaching residue, which is roasted from the molybdenum concentrates with addition of equivalent mass of Ca(OH)₂ at the roasting temperature of 650 °C for 90 min, the leaching conditions are set up as follows: concentration of sulfuric acid of 70 g/L, leaching at 90 °C for 120 min, ratio of liquid to solid 5:1. It can be concluded that molybdenum is hard to be lost or volatilized during the roasting process. The sulfur-fixing rate is 91.49%, which indicates that little sulfur is volatilized into the smoke as SO₂, and it can be absorbed by alkali. After acid leaching, the surplus grade of molybdenum attains 0.2%, the leaching rate of molybdenum reaches 99.12%, and the total loss is only 0.88% in the whole process.

The phase compositions of calcine and the leaching residue are studied by XRD analysis as shown in Fig. 11.

![Fig. 10](image_url) Quality flow chart of of calcium-based roasting and acid leaching process

![Fig. 11](image_url) XRD patterns of leaching residue obtained with acid leaching

MoS₂ disappears after roasting, and the main phases of calcine are CaMoO₄ and CaSO₄. The characteristic peaks of CaMoO₄ disappear, and the peaks of CaSO₄ are markedly strengthened after acid leaching, indicating that calcium molybdate is completely dissolved. The main components of the leaching residue are CaSO₄, gypsum (CaSO₄·2H₂O) and tacle (Mg₃(Σ_SiO₁₀)(OH)₃). As a conclusion, molybdenum in low-grade molybdenum concentrate can be recycled completely by calcification roasting–acid leaching process.

4 Conclusions

1) During the roasting process of molybdenum concentrate with calcium-based additives, additives are able to react with MoO₃ and SO₂ to form CaMoO₄ and CaSO₄. Adding Ca(OH)₂ can achieve the best roasting effects and sulfur-fixing rate, which is followed by CaO, and then CaCO₃. The microstructure of calcine shows that the intact grains of CaMoO₄ and CaSO₄ are formed with the addition of Ca(OH)₂, while adding CaO or CaCO₃ is unable to achieve the above effect.

2) Higher roasting temperature contributes to the formation of CaMoO₄ while it causes the decrease of both sulfur-fixing rate and retention rate of molybdenum. The phase evolution indicates that MoS₂ starts to be oxidized at 450 °C, while CaMoO₄ and CaSO₄ start to form at 500 °C, and the main phase compositions of calcine are CaMoO₄ and CaSO₄ at temperatures of 600–650 °C, at which the calcification reaction is nearly completed.

3) With increasing the dosage of Ca(OH)₂, the retention rate of molybdenum and the sulfur-fixing rate tend to grow with more acid consumed. The appropriate mass ratio of Ca(OH)₂ to molybdenum concentrate is 1:1. By roasting the molybdenum concentrate at 650 °C for 90 min with appropriate dosage of Ca(OH)₂, the retention rate of molybdenum during the roasting process achieves 100%, the sulfur-fixing rate attains 92.92%, and the leaching rate of molybdenum achieves 99.12%.

References

低品位钼精矿钙化焙烧的反应机理

甘 敏，范晓慧，陈许玲，吴程骞，季志云，王送荣，汪国靖，邱冠周，姜 涛

中南大学 资源加工与生物工程学院，长沙 410083

摘要：研究了钙基添加剂对低品位钼精矿焙烧性能的影响。结果表明，钙基添加剂可与钼精矿反应生成 CaSO₄ 和 CaMoO₄。450℃时 MoS₂开始氧化，500℃以上生成 CaMoO₄和 CaSO₄。600~650℃时钙化反应基本完成；进一步提高焙烧温度有利于 CaMoO₄的生成，但会降低焙烧过程固硫率和钼保留率。钙基添加剂焙烧效果依次为 Ca(OH)₂>CaO>CaCO₃。随着 Ca(OH)₂用量的增加，钼保留率和固硫率均呈上升趋势，但过多的钙基添加剂会使酸浸过程硫酸的消耗增加，Ca(OH)₂与钼精矿适宜的质量比为 1:1。在 650℃下焙烧 90 min 时，低品位钼精矿钙化焙烧过程中钼保留率为 100％，固硫率为 92.92％，经硫酸浸出后钼的浸出率达到 99.12％。

关键词：钼精矿；钙化焙烧；反应机理；热力学研究；相变

(Edited by Wei-ping CHEN)