ABSTRACT: The investigation of the dielectric properties of bastnasite concentrate has critical directing centrality for the microwave roasting process of bastnasite concentrate. The dielectric properties are correlated with information such as thermogravimetry—differential scanning calorimetry and temperature rise curves. This combination permits a targeted study of the mechanism of the microwave roasting process, providing new evidence about the unique conditions of this microwave roasting process. This work also explores the response surface methodology based on a central composite design to optimize the microwave non-oxidative roasting process. Single-factor tests were conducted to determine the suitable range of factors such as the content of activated carbon, holding time, and roasting temperature. The interactions between parameters were investigated through the analysis of variance method. It was indicated that the models are available to navigate the design space. Also, the optimal roasting temperature, content of activated carbon, and holding time were 1100 °C, 20%, and 21.5 min, respectively. Under these conditions, the decomposition rate of bastnasite concentrate (hereinafter to be referred as DRBC) and the oxidation rate of cerium (hereinafter to be referred as ORC) was 99.8% and less than 0.3%, respectively. The new non-oxidizing roasting method significantly shortens the roasting time, reduces the energy consumption, and has great significance for industrial applications.

INTRODUCTION

Bastnasite concentrate is the most important rare-earth mineral. More than 70% of rare-earth products obtained by smelting and separation in industrial production are from bastnasite concentrate.1 Oxidative roasting decomposition of bastnasite is a mature decomposition technology for industrial applications.2 However, this method has the following drawbacks: (1) conventional electric heating or natural gas heating has high energy consumption, and the roasting process has a low energy efficiency; (2) while bastnasite decomposes, the oxidation rate of cerium (ORC) is over 96%.3 Also, (3) the leaching efficiency of Ce(IV) is always lower than that of La(III) and Nd(III)4 because Ce(IV) does not dissolve in dilute hydrochloric acid.5 When the roasting ore is dissolved in concentrated hydrochloric acid, the concentrated hydrochloric acid reduces Ce(IV) to Ce(III) and simultaneously oxidizes the chloride ion to chlorine gas which is toxic and affects the health of the operator.6 To suppress the generation of chlorine gas, it is necessary to add a reductant, which increases the production cost and affects the quality of rare-earth products. All rare-earth elements (REEs) can maintain their trivalent forms if Ce(III) is not oxidized to Ce(IV), in which case, it is not necessary to add the reductant. Therefore, the non-oxidizing roasting method can significantly reduce production costs, and less impurities enter the solution.5 Thus, a new efficient and environmentally friendly method must be developed.

Microwave irradiation heating, as an efficient heating method, has been applied in metallurgy and has become a new type of green metallurgy method.7,8 However, the dielectric properties of bastnasite concentrate and of the
mixture of bastnasite concentrate and activated carbon in the microwave field have not been investigated. Dielectric properties are the critical factors that determine how microwave energy is transmitted, reflected, and absorbed. Thus, the investigation of the dielectric properties involved in the roasting process with temperature can provide important information to analyze the changes that occurred during the roasting process.

In our previous studies, these roasting process experiments are carried on a single-factor approach, the mutual effects of significant parameters influencing the rate of decomposition of bastnasite concentrate and oxidation of cerium have not been investigated in depth. Response surface methodology (RSM) using a central-composite design (CCD) is widely used to characterize the mutual effects of various parameters. Therefore, the interaction between the two parameters (the content of activated carbon and holding time) was explored by evaluating the RSM. Two mathematical models for response prediction were developed based on the two parameters. The response surface analysis and optimization resulted in an optimized solution for the effective decomposition of the bastnasite concentrate, while cerium remained in its trivalent form. This paper aims to investigate the heating and dielectric properties of the mixture of bastnasite concentrate and activated carbon during the microwave roasting process and to determine the optimal microwave roasting conditions using RSM. The investigation of the heating and dielectric properties is conducive to expanding the roasting mode of the bastnasite concentrate. This paper also proposes the microwave roasting mechanism of bastnasite concentrate.

**RESULTS AND DISCUSSION**

**Microwave Heating Characteristics Analysis.** As shown in Figure 1, the effects of the different contents of activated carbon on the heating rate of bastnasite concentrate were studied at a microwave power of 1200 W and a frequency of 2.45 GHz. The results indicated that the heating rate of bastnasite concentrate was very slow. When the content of activated carbon was more than 10%, the temperature of the mixture rapidly rose to 1100 °C. The temperature rise curves are similar to those reported by other researchers. It is generally accepted that a higher holding temperature helps to accelerate the decomposition reaction of the bastnasite concentrate. Therefore, the optimal holding temperature was set to 1100 °C. It can be seen that the temperature rise curves of the mixture are clearly in two stages, the heating rate after exceeding 427 °C is significantly higher than that of the heating rate before 427 °C. This is because the absorbing properties of the bastnasite concentrate change with the temperature and the nature of the bastnasite concentrate.

The above phenomena should be further analyzed together with the results of thermogravimetry (TG) and differential scanning calorimetry (DSC) measurements. As shown in Figure 2, bastnasite concentrate starts to decompose at 427 °C, which agrees well with the temperature of the deflection point of the heating curve in Figure 1. The decomposition products of bastnasite concentrate are RE₂O₃ and REF₃ as shown in reaction eqs 1 and 2. It can be inferred that the decomposition products of bastnasite concentrate may affect the heating properties of the mixture. Therefore, as the phase change of bastnasite concentrate occurs, the temperature rise curve of the mixture may show a robust change.

$$2REF_2RE_2(CO_3)_3 = RE_2O_3 + 3REOF + REF_3 + 6CO_2$$  
(1)

$$3REOF = RE_2O_3 + REF_3$$  
(2)

The responsiveness of minerals to microwaves at different temperatures ought to be decided by considering the dielectric properties of the minerals. Therefore, the dielectric properties of bastnasite concentrate and the mixture of bastnasite concentrate and activated carbon require further investigation.

Figure 3 shows the dielectric properties (ε', ε″, and tan δ) of bastnasite concentrate and the mixture of bastnasite concentrate and activated carbon as a function of temperature. The relative dielectric constant (ε') reflects the energy conversion ability from the microwave field to be absorbed in the minerals. Relative dielectric loss factor (ε″) represents the degree of loss of material to the external electric fields. The ability of the minerals to transform microwave power into thermal energy is expressed as the tangent of dielectric loss (tan δ), as shown in eq 3. In general, minerals that have a high tangent of dielectric loss can be rapidly heated by microwave.

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'}$$  
(3)

As shown in Figure 3, the dielectric properties of bastnasite concentrate and the mixture of bastnasite concentrate and
activated carbon increase as temperature increases. In Figure 3a, the relative dielectric constant \( (\varepsilon') \) of bastnasite concentrate is significantly lower than those of the mixture of bastnasite concentrate and activated carbon. Specifically, the range of relative dielectric constant of bastnasite concentrate is 1.831–2.201, the variation range of the mixture of 10% activated carbon added is 2.381–2.895, and the variation range of the mixture of 20% activated carbon added is 2.53–3.199. The above information indicates that activated carbon effectively improved the dielectric properties of bastnasite concentrate.

This can be seen in Figure 3b,c, when the roasting temperature is below the initial decomposition temperature (427 °C), the relative dielectric loss factor and tangent of dielectric loss of bastnasite concentrate are below that for the mixture of bastnasite concentrate and activated carbon. However, the relative dielectric loss factor and tangent of dielectric loss of the mixture of bastnasite concentrate and activated carbon are close to those of the bastnasite concentrate as the temperature rises above 427 °C. When the roasting temperature was higher than 427 °C, the bastnasite concentrate begins to decompose, which is consistent with the sudden change in temperature of the dielectric properties. As a result, the conversion of microwave energy into heat is significantly enhanced when bastnasite concentrate is decomposed. One possible reason for this is that bastnasite concentrate was decomposed to \( \text{RE}_2\text{O}_3 \) and \( \text{REF}_3 \), thus improving the dielectric properties.

Hence, it is sensible to assume that the mixture of bastnasite concentrate and activated carbon is capable of converting microwave energy into heat mainly due to the presence of activated carbon, \( \text{RE}_2\text{O}_3 \), and \( \text{REF}_3 \).

To verify the above inference, the temperature rise curve of rare-earth oxide heating by microwave irradiation was studied. It can be seen from Figure 4 that lanthanum–cerium mixed oxide, praseodymium–neodymium mixed oxide, and mixed rare-earths oxide have a similar rise curve with the mixture of bastnasite concentrate and activated carbon. The deflection point temperatures of lanthanum–cerium mixed oxide and praseodymium–neodymium mixed oxide are 327 and 453 °C, respectively. However, the deflection point temperature of mixed rare-earth oxides is 418 °C. Excluding temperature measurement errors of the microwave equipment, the deflection point temperature of the mixture of bastnasite concentrate and mixed rare earth oxides is the same as the decomposition temperature of the bastnasite and the deflection point of the tangent of dielectric loss. It can be seen that the mixture of bastnasite concentrate and activated carbon can effectively convert microwave energy into heat due to the presence of activated carbon, \( \text{RE}_2\text{O}_3 \), and \( \text{REF}_3 \) in the mixture.
be inferred that a rare-earth oxide has a good absorbing microwave performance. The deflection point on the temperature rise curve is due to the formation of the rare-earth oxide. Due to the coexistence of activated carbon and rare-earth oxides, the mixture could quickly heat up to 1100 °C in a short time and also could maintain the roasting temperature of 1100 °C.

In summary, the ability to quickly heat the mixture of bastnasite concentrate and activated carbon after 427 °Ci s largely dependent on the efficient response of the activated carbon and rare-earth oxides in the mixture to microwaves.

**Effect of Different Contents of Activated Carbon on ORC.** As shown in Figure 5, the effects of holding time on ORC were studied. When the content of activated carbon was 10%, the results indicated that ORC at time spans of 5, 20, and 40 min were 0.2, 26.2, 54.9%, respectively. When the content of activated carbon was 15%, the oxidation rate began to increase after the holding time exceeded 20 min. When the content of activated carbon was 20%, the oxidation rate was less than 1.3% within 40 min, and it can be considered that most of Ce(III) was not oxidized to Ce(IV). Thus, the content of activated carbon is positively correlated with the holding time for maintaining Ce(III).

**Effect of Holding Time on DRBC and ORC.** The holding time range was selected from 0 to 50 min and is shown in Figure 6. With the gradual extension of holding time, the decomposition rate was gradually increased and reached 99.3% at 20 min. When the holding time exceeded 20 min, the decomposition rate decreased obviously. However, the decomposition rate of bastnasite concentrate (DRBC) was slightly increased when the heating time was up to 40 min. Also, ORC was constant and remained below 0.3% in the first 30 min. It can be assumed that Ce₂O₃ was not oxidized to CeO₂. Nevertheless, the ORCs were 1.3 and 15.6% at holding times of 40 and 50 min, respectively. When oxidation of trivalent cerium occurs, it indicates that the activated carbon has been exhausted.

Scanning electron microscopy (SEM) analysis of roasting ore at 20 and 40 min is shown in Figure 7A,B, respectively. With the extension of the holding time, the roasted ore exhibited severe sintering, which coincided with the decrease in DRBC at the holding time of 30 min. After 30 min, the decomposition rate was slightly increased. This is because ORC increased as the holding time increased. The complex form of Ce⁴⁺ with F⁻ could be [CeFₓ]⁴⁻ and the complex [CeFₓ]⁴⁻ can facilitate the leaching of roasted ore in
hydrochloric acid solution. This in turn is reflected in the increase in decomposition rate.\textsuperscript{13}

Optimization of Experimental Conditions Based on RSM. RSM is a statistical method to solve multivariate problems by using reasonable experimental design methods and obtaining certain data through experiments, using multiple quadratic regression equations to fit the functional relationship between factors and response values, and seeking the optimal process parameters through the analysis of the regression equations.\textsuperscript{16–19} Therefore, we use the RSM to optimize the microwave non-oxidation roasting process.

According to the above single factor test results, when the content of activated carbon was more than 10%, the mixture could be heated to 1100 °C within 15 min. However, when the content of activated carbon was higher than 20%, the cost would be significantly increased. In order to obtain a high decomposition rate without Ce(III) being oxidized, the holding time needs to be more than 10 min to ensure that the bastnasite concentrate can be effectively decomposed. The holding time also needs to be less than 40 min to ensure that Ce(III) was not oxidized. Therefore, the variation interval of the holding time was set to 10–40 min, and the variation interval of activated carbon content was set to 10–20% to conduct the experimental studies.

The model uses the codes $Y_1$ for DRBC and $Y_2$ for ORC. The independent variables in the CCD model were coded as (holding time) $X_1$ and (the contents of activated carbon) $X_2$, respectively; the high, center, and low levels of $X_i$ are 1, 0, and $-1$, respectively, as shown in Table 1.

Table 1. Independent Variables for Selected Ranges and Corresponding Levels

| independent variables | factor level |
|-----------------------|--------------|
| $X_1$ holding time (min) | 3.7868 | -1 | 0 | 1 | +1 |
| $X_2$ contents of activated carbon (%) | 7.9289 | 10 | 15 | 20 | 22.0711 |

The results of 13 experimental runs are presented in Table 2. The experimental results were calculated using Design Expert 8.0.5 software, and $Y_1$ and $Y_2$ models were fitted by multiple linear regression. Design Expert 8.0.5 software establishes reliable predictive models by statistically analyzing the response variables to determine the optimal operating conditions.

Table 3. $Y_2$ Response Surface Variance Analysis (ANOVA) and Significance Test

| source | sum of squares | df | mean square | F-value | p-value |
|--------|---------------|----|-------------|---------|---------|
| model  | 97.25         | 6  | 16.21       | 148.83  | <0.0001 | significant |
| $X_1$  | 11.7          | 1  | 11.7        | 107.42  | <0.0001 |
| $X_2$  | 16.82         | 1  | 16.82       | 154.44  | <0.0001 |
| $X_1X_2$ | 5.52        | 1  | 5.52        | 50.71   | 0.0004  |
| $X_1^2$ | 51.99        | 1  | 51.99       | 477.37  | <0.0001 |
| $X_2^2$ | 17.45        | 1  | 17.45       | 160.22  | <0.0001 |
| residual | 5.62        | 6  | 0.93        | 1.24    | 0.2389  |
| lack of fit | 0.21   | 2  | 0.11        | 0.4701  | not significant |
| pure error | 0.45  | 4  | 0.11        |         |         |
| cor total | 97.9     | 12 |             |         |         |

The model $F$-values of 148.83 and 47.72 imply that the models of DRBC (model 1) and ORC (model 2) are significant. There is only a 0.01% chance that a “model $F$ value” this large could occur due to noise. Values of "prob > $F""$ less than 0.0500 indicate that the model terms are significant. In this case, $X_1$, $X_2$, $X_1X_2$, $X_1^2$, $X_2^2$, $X_1X_2$ (model 1) and $X_1$, $X_2$, $X_1X_2$ (model 2) are significant model terms. Values greater than 0.1000 indicate that the model terms are not significant. The "lack of fit $p$-values" of 0.4701 (model 1) and 0.2389 (model 2) imply that the "lack of fit $p$-value" is not significant, which indicates that the suggested model fits well. The "lack of fit $F$-values" of 0.92 (model 1) and 2.15 (model 2) implies that the lack of fit is not significant relative to the pure error. There are 47.01% (model 1) and 23.89% (model 2) chances that "lack of fit $F$-value" this large could occur due to noise. The results of model 1 summary statistics showed the closed $R^2$ value of 0.9933 and $R_{adj}$ value of 0.9867, and the results of model 2 summary statistics showed the closed $R^2$ value of 0.9408 and $R_{adj}$ value of 0.9211, which indicated their dependability in the prediction of response. The $R_{pred}$ values
of 0.9597 (model 1) and 0.8535 (model 2) are in reasonable agreement with the $R_{adj}^2$ of 0.9867 (model 1) and 0.9211 (model 2), respectively. A ratio greater than 4 is desirable. The ratios of model 1 (29.640) and model 2 (21.855) indicate an adequate signal. Models 1 and 2 can be used to navigate the design space. The mathematical models 1 and 2 are given by eqs 4 and 5.

$$Y_1 = 89.20367 - 0.66396X_1 + 0.98806X_2 + 0.090138X_1X_2 + 0.010191X_1^2 - 0.063350X_2^2 - 1.48943X_1 \times X_2^2$$

(4)

$$Y_2 = 4.46174 + 2.98698X_1 + 0.16864X_2 - 0.14333X_1X_2$$

(5)

Figures 8 and 10 show a comparison of the predicted and actual values of DRBC and ORC, respectively. The results showed that the experimental results were distributed relatively close to the straight line, and there was a good agreement between the predicted and experimental results. Thus, the CCD models were consistent with the experimental data. It was shown that the predicted model could accurately study the experimental parameters. As shown in Figures 9 and 11, almost all standardized residuals were randomly dispersed in the figure by about ±2.00. From the studies, the predictive models were proposed that exhibited good consistency with the experimental data.

Figure 12 shows the effect of the interaction between the contents of activated carbon and holding time on DRBC. The region highlighted in red shows the highest DRBC. It could be seen from the response surface diagram that with the holding time increased, DRBC increased first and then decreased. Also, with the increase in the contents of activated carbon, DRBC tended to increase to 99.9%. The highest point on the response surface corresponds to the optimum holding time and the contents of activated carbon.

Figure 13 shows the effect of the interaction between the contents of activated carbon and holding time on ORC. The blue region shows the lowest oxidation rate. It could be seen from the response surface diagram that as the holding time increased, ORC decreased first and then increased.

Table 4. $Y_2$ Response Surface Variance Analysis (ANOVA and Significance Test)

| source     | sum of squares | df | mean square | F-value | p-value |
|------------|---------------|----|-------------|---------|---------|
| model      | 4055.23       | 3  | 1351.74     | 47.72   | <0.0001 significant |
| $X_1$      | 1260.95       | 1  | 1260.95     | 44.51   | <0.0001 |
| $X_2$      | 2332.02       | 1  | 2332.02     | 82.32   | <0.0001 |
| $X_1X_2$   | 462.25        | 1  | 462.25      | 16.32   | 0.0029  |
| residual   | 254.96        | 9  | 28.33       |         |         |
| lack of fit| 185.86        | 5  | 37.17       | 2.15    | 0.2389  not significant |
| pure error | 69.1          | 4  | 17.27       |         |         |
| cor total  | 4310.19       | 12 |             |         |         |

https://doi.org/10.1021/acsomega.1c01218

ACS Omega 2021, 6, 10486–10496
increased, the oxidation rate gradually increased. With the contents of activated carbon gradually increased, ORC tended to decrease slowly. It is indicated that the holding time is the main influencing factor of the cerium oxidation rate. Thus, shorter holding times and more activated carbon added corresponds to the lowest point on the response surface.

RSM Prediction and Experimental Verification. The optimization process of the response surface experiment was verified by experiments. Because the accuracy of experimental equipment to control holding time was limited, the holding time \((X_1)\) in the optimal experimental results was set to 21.3 and 21.5 min, respectively. The results are shown in Table 5. The relative error between the actual value and the predicted value was about 1%, which indicated that the experimental results could be predicted accurately by response surface analysis and optimization.

According to optimization results and actual experimental data, the optimal roasting condition was determined as follows: roasting temperature of 1100 °C, contents of activated carbon

Figure 11. Plot of the internal residuals vs the number of experimental runs.

Figure 12. Two-factor interaction and its influence on DRBC.
of 20%, and holding time of 21.5 min. DRBC and ORC were 99.8% and less than 0.3%, respectively.

**XRD Analysis of Non-oxidative Roasting Ore.** The non-oxidative roasting ore used for X-ray diffraction (XRD) analysis was obtained under the optimal roasting conditions. As shown in **Figure 14**, the XRD pattern of the non-oxidative roasting ore demonstrated that the main phase was rare-earth oxides (represented by Nd$_2$O$_3$ and CeO$_{1.675}$ in the XRD pattern). Moreover, no diffraction peaks of bastnasite and parisite were found, indicating that bastnasite and parisite had been completely decomposed into earth oxides.

| solution number | $X_1$ (min) | $X_2$ (%) | $Y_1$ predicted value (%) | $Y_1$ actual value (%) | $Y_2$ predicted value (%) | $Y_2$ actual value (%) |
|-----------------|-------------|-----------|--------------------------|------------------------|--------------------------|------------------------|
| 1               | 21.33       | 20        | 99.0000                  | 99.8                   | <0.3                     |                        |
| 2               | 21.58       | 20        | 99.0755                  | 99.6                   | <0.3                     |                        |

**CONCLUSIONS**

In this paper, a microwave roasting mechanism is presented for the mixture of bastnasite concentrate and activated carbon. The effective heating of the mixture of bastnasite concentrate
and activated carbon by microwave is largely dependent on the efficient response of the activated carbon and rare-earth oxides to microwaves. Due to the coexistence of activated carbon and rare earth oxides, the mixture could quickly heat up to 1100 °C in a short time and also could maintain the roasting temperature of 1100 °C. The microwave non-oxidative roasting method is not only significantly shortening the roasting time but also reducing the energy consumption to roast bastnasite concentrate by microwave irradiation, more importantly realizing the decomposition of bastnasite concentrate and preventing Ce(III) oxidation to Ce(IV). DRBC and ORC were 99.8% and less than 0.3%, respectively. The non-oxidative decomposition of bastnasite concentrate removes the greatest hazards and reduces energy consumption.

## EXPERIMENTAL SECTION

### Raw Ores and Reagents.

The bastnasite concentrate used in this experiment was supplied by China Northern Rare Earth (Group) Hi-Tech Co. Ltd. and was dried at 110 °C for 4 h to remove the free moisture water. The analytical grade reagents were used in the experiment, including activated carbon and hydrochloric acid. All aqueous solutions were prepared with distilled water. The main chemical components of bastnasite concentrate were analyzed and are listed in Table 6.

Table 6. Chemical Composition of Bastnasite Concentrate (Mass Fraction, %)

| composition | REO | CaO | Al₂O₃ | PbO | ZnO | PO₄³⁻ | SrO | F | MgO | ThO₂ |
|-------------|-----|-----|-------|-----|-----|-------|-----|---|-----|------|
| content (%) | 55.86 | 10.61 | 0.19 | 0.19 | 0.012 | 1.58 | 1.50 | 3.43 | 0.35 | 0.10 |

As shown in Figure 15, the XRD pattern of bastnasite concentrate demonstrated that the main phase was bastnasite and parisite (represented by CeFCO₃ and CaCe(CO₃)₂F in the XRD pattern). It was consistent with the analysis results of the chemical components shown in Table 6.

![Figure 15. XRD pattern of bastnasite concentrate.](image)

### Dielectric Testing Equipment and Measurement Principles.

Currently, there are three major methods used to measure the dielectric properties of powder samples, such as the opening method, resonant cavity perturbation method, and free space method. Among them, the resonant cavity perturbation method is a comparatively precise method to measure the dielectric properties. Therefore, we chose the cavity perturbation method to measure the sample’s dielectric properties. The measuring principle of the cavity perturbation method is based on the determination of the quality factor (QF) and the resonant frequency before and after loading, and the calculation of the dielectric properties based on the difference between the QF and the resonant frequency of the sample before and after loading.

The dielectric properties testing system and the monomode microwave equipment worked in this series of experiments were from the Key Laboratory of Unconventional Metallurgy, Ministry of Education, Kunming University of Science and Technology, China. The dielectric properties testing system is shown in Figure 16a. It consists of four main components: vector network analyzer (Agilent-N5230C, MYWAVE), resonant cavity (TM₀ⁿ₀), a computer with HFSS simulation software, and temperature control. The dielectric properties were tested using the dielectric properties testing equipment, the microwave frequency was set to 2450 MHz, setting the test temperature from 25 to 700 °C. The interval of test temperature was 50 °C/step. The mixture of bastnasite concentrate and activated carbon was placed inside a quartz tube, and the mass and volume of the mixture were measured to ensure that the apparent density of each test sample is the same. The procedure for measuring the dielectric properties is as follows: first, the device was adjusted to minimize the error, and the unloaded QF of the resonant cavity (TM₀ⁿ₀) is approximately 10,000; second, an empty quartz tube was placed in the resonant cavity (TM₀ⁿ₀), and the resonant frequency and QF of the resonant cavity (TM₀ⁿ₀) were recorded by the Agilent N5230C vector network analyzer; third, the mixture of bastnasite concentrate and activated carbon was placed in a quartz tube and heated by an induction furnace. Once the preset temperature was reached, the quartz tube was swiftly raised into the resonant cavity (TM₀ⁿ₀), after which the Agilent N5230C vector network analyzer recorded the QF and the resonant frequency; finally, the HFSS simulation software calculated the dielectric loss tangent and the complex permittivity by analyzing the QF and the resonant frequency that had been recorded.

Regarding the maximum temperature, the results of the dielectric properties are usually only available up to a few hundred degrees. This temperature limitation is mainly due to the increased radiation loss at higher temperatures but also due to the practical limitations of commercially available measurement equipment.

### Experimental Process and Analysis.

The monomode microwave equipment is shown in Figure 16b. Experiments of roasting decomposition of bastnasite concentrate with microwave heating were conducted at a power of 1200 W and a frequency of 2.45 GHz. The bastnasite concentrate was mixed with activated carbon by mixed grinding. The mixture was placed in a 50.0 mm diameter corundum crucible and then put in the center of the box microwave furnace for roasting. The K-type thermocouple was inserted into the center of the mixture in the microwave roasting process, and the temperature was measured continuously. After the roasting experiment, the corundum crucible was removed and the roasted ore was ground for leaching.

### Experimental Analysis.

XRD analysis was carried out on the PW-1700 X-ray diffractometer (Philips, Netherlands) with Cu Kα source (k = 1.5418 Å) operating at 40 kV with a scanning speed of 0.2°/min. The microstructures of bastnasite...
concentrate and roasting ore were analyzed using the Sigma-500 field-emission scanning electron microscope (Zeiss, Germany), and the mineral composition analysis was analyzed using an XFlash-6160 spectrometer (Brook). The amounts of REEs in the leaching filtrate were determined using inductively coupled plasma atomic emission spectrometry and presented by oxides. The simultaneous thermal analyzer of STA-449C was employed to achieve the curve of TG−DSC. The bastnasite concentrate was placed in an alumina crucible and was heated to 1000 °C from 20 °C at the rate of 10 °C/min. The amounts of Ce⁴⁺ in roasted ore were determined by titration with ferrous ammonium sulfate without the addition of perchloric acid.²⁸ DRBC were expressed by hydrochloric acid leaching experiments carried out under the condition that is 9.0 mol/L HCl, temperature 90 °C, time 60 min, liquid−solid 20:1, and stirring rate 300 rpm.¹³ DRBC (μ) and ORC (φ) were calculated with the following equations

$$\mu = \frac{C_1 \times L}{C_2 \times S} \times 100\%$$  \hspace{1cm} (6) $$\phi = \frac{\omega_1 \times m_1}{\omega_2 \times m_2} \times 100\%$$  \hspace{1cm} (7)

where μ and φ are DRBC and ORC, respectively; m₁ is the mass of the roasted ore, m₂ is the mass of the bastnasite concentrate; ω₁ is the mass fraction of Ce in the bastnasite concentrate, ω₂ is the mass fraction of Ce⁴⁺ in the roasted ore; C₁ represents the concentration of REEs in leaching filtrate, C₂ represents the concentration of REEs in roasted ore; S is the mass of roasted ore, and L is the volume of hydrochloric acid solution.

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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge funding support from the Key Program of the National Natural Science Foundation of China (grant number 51634005), the Key Program of the Natural Science Foundation of Inner Mongolia Autonomous Region of China (grant number 2016ZD03), and the Key Program of the Natural Science Foundation of Inner Mongolia Autonomous Region of China (grant number 2017MS0210).
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