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CARBOTHERMIC REDUCTION KINETICS OF ILMENITE CONCENTRATES CATALYZED BY SODIUM SILICATE AND MICROWAVE-ABSORBING CHARACTERISTICS OF REDUCTIVE PRODUCTS

Carbothermic reduction kinetics of ilmenite concentrates catalyzed by sodium silicate were investigated; the reduction degree of ilmenite concentrates reduction reaction was determined as $R = 4/7(16y + 56x)(\Delta W_\Sigma - f_{A\text{-}P}W)/(16y + 56x + 112)$. The results show that the reaction activation energy of initial stage and later stage is 36.45 and 135.14 kJ/mol, respectively. There is a great change in the reduction rate at temperatures of 1100 and 1150 °C; the catalysis effect and change of reduction rate were evaluated by TG and DSC curves of sodium silicate. Microwave-absorbing characteristics of reduction products were measured by the method of microwave cavity perturbation. It was found that microwave absorbing characteristics of reduction products obtained at temperatures of 900, 1100 and 1150 °C have significant differences. XRD characterization results explained the formation and accumulation of reduction product Fe, and pronounced changes of microwave absorbing characteristics due to the decrease of the content of ilmenite concentrates.

Keywords: sodium silicate; ilmenite concentrates; catalytic reduction; kinetics; microwave absorbing characteristics.

The mineral ilmenite ($FeTiO_3$) is the main source of titanium dioxide which is widely used as a white pigment. The common treatment method is thermal reduction of ilmenite to form TiO_2 and elemental iron followed by a leach to remove the iron. The reduction of ilmenite concentrate plays an important role in the titanium industry. It has been well documented that ilmenite concentrate usually needs high reductive temperature or needs additives to improve its reactivity when it is directly reduced [1,2]. Over the past several decades, many research studies have been done on the mechanism and kinetics of the reduction of different ilmenite. Wouterlood [3] investigated the reduction of ilmenite with carbon at temperatures of 900 to 1200 °C and found the reaction consisted of two stages: the fast first stage indicating the reduction of ferric to ferrous iron, and a slower second stage in which ferrous iron was reduced to metallic iron.

Researches have shown that carbothermic reduction of ilmenite at temperatures below 1200 °C produces metallic iron and reduced form of oxides (Ti_nO_{2n-1}) [4,5]. Carbothermic reduction of ilmenite and rutile was investigated by Welham and Williams [6] at temperatures up to 1500 °C, indicating that the reduction of rutile was found to proceed through a series of oxides Ti_nO_{2n-1} until the formation of Ti_3O_5. Kucuk-karagoz [7] investigated the reduction of ilmenite concentrate with graphite under argon gas between 1250 and 1350 °C, showing that reduction rates increased with increasing temperature and decreasing particle size. Dewan [8] studied carbothermal reduction of ilmenites of different grades and synthetic rutile in different gas atmospheres. The carbothermal reduction of primary ilmenite concentrate was faster in hydrogen and occurred at a lower temperature than in argon and helium. The reduction in argon and helium had about the same rate and extent [8]. Eungyeul [9,10] researched the reduction of titania-ferrous ore by H_2 and CO; Satoshi [11] also investigated the reduction kinetics of natural ilmenite ore with carbon monoxide and found the reduction rate

increased with increasing temperature, the rate and the degree of reduction depended on the formation of a metallic shell of iron [9-11]. The reactivity of ilmenite can also be improved by using a pre-oxidization process, increasing the rate of ilmenite reduction and the rate of leaching [12-15]. Zhang and Ostrovski [15] investigated the effects of pre-oxidation and sintering on the phase composition, specific surface area, morphology and reducibility of ilmenite concentrates. It was demonstrated that both pre-oxidation and sintering increased the temperature required to reduce titanium oxides. Pre-oxidization is now a broadly adopted practice in the processing of ilmenite ore for production of TiO_2 pigment and metallic titanium. Wang and Yuang [16] described the reduction degree and rate of Bama ilmenite concentrate by graphite at temperatures from 850 to 1400 °C. The reduction degree and reaction rate of the ilmenite increased with increasing temperature. The higher the temperature was, the faster the reaction rate was. The reduction degree of the ilmenite decreased due to the presence of impurities.

The ilmenite deposit in Panzhihua region, Sichuan, China accounts for 35% of the titanium resource in the world, and for approximately of 92% in China [17]. So, it is very important to utilize the ilmenite resources efficiently for the development of the titanium industry. However, due to the higher contents of CaO and MgO and complex mineralogy in ilmenite in Panzhihua region, it is very difficult to upgrade the ilmenite to titanium-rich slag, which limits the development and utilization of ilmenite deposit in Panzhihua region; it is urgent to develop new processing technologies of ilmenite concentrates [13,18-20].

In recent years there has been a growing interest in microwave heating in mineral treatment. Advantages in utilizing microwave technologies for processing materials include penetrating radiation, controlled electric field distribution and selective and volumetric heating [21]. Because of these advantages, a number of potential applications of microwave processing materials have been investigated, such as microwave assisted ore grinding, microwave assisted carbothermic reduction of metal oxides, microwave assisted drying and anhydration, microwave assisted mineral leaching, microwave assisted roasting and smelting of sulphide concentrate, microwave assisted pretreatment of refractory gold concentrate, microwave assisted spent carbon regeneration, coke

making and activated carbon production, and microwave assisted waste management, etc. [22-31].

For microwave processing of ilmenite, Itoh *et al.* described the microwave oxidation of rutile extraction process, in which rutile is extracted from a natural ilmenite ore by oxidation and magnetic separation followed by leaching with diluted acid [32]. Kelly and Rowson investigated microwave reduction of oxidized ilmenite concentrate [33]. Tong *et al.* evaluated the economic values of industrial applications of carbothermic reduction of metals oxide by microwave heating, showing that the cost is lowered about 15-50% compared to that of conventional method [34]. Cutmore *et al.* investigated dielectric properties of some minerals [35]. Microwave absorbing characteristics of ilmenite concentrate with different proportions of carbonaceous reduction agents were investigated by the authors' group [20], which further confirms the feasibility of microwave reduction of ilmenite concentrate. All of these investigations present encouraging results.

However, to the best of our knowledge, there is little information about carbothermic reduction kinetics of ilmenite concentrate by using catalyst and microwave absorbing characteristics of reactants and products during microwave irradiation, resulting in difficulty of investigations on the interaction mechanism between microwaves and materials, which limits the application of microwave heating technology in industry. So, there is an urgent need to investigate microwave-absorbing characteristics of materials and accumulation of data of dielectric properties, in order to prompt applications of microwave heating in all different kind of fields.

The objective of the present study is to investigate carbothermic reduction kinetics of ilmenite concentrate synergistic catalyzed by sodium silicate and microwave-absorbing characteristics of reductive products measured by the method of microwave cavity perturbation.

EXPERIMENTAL

Materials

The raw material, ilmenite, was obtained from Panzhihua (Sichuan province, PR China). The chemical compositions of ilmenite and proximate analysis of coke were listed in Tables 1 and 2, respectively.

It can be seen from Tables 1 and 2 that both ilmenite and coke contain volatiles; especially for

Table 1. Chemical compositions of ilmenite concentrate

Component	TFe	TiO_2	CaO	MgO	SiO_2	Al_2O_3	S
Content, mass%	32.18	47.85	1.56	6.56	5.6	3.16	≤0.1

Table 2. Proximate analysis of coke

Water content	Ash	Volatile	Fixed carbon	Total sulfur	Calorific value
1.93%	27.80%	1.41%	70.80%	2.68%	23.64 MJ/Kg

coke, the amount content of volatile, sulfur and water is more than 6.02%. If this amount were also calculated as weight of oxygen loss, it would lead to calculation errors of reduction degree by using the method of weight loss. So, calibrations of weight loss fraction at different reduction temperatures by using coke as reduction agent were investigated, in order to increase the calculation accuracy of reduction degree of ilmenite concentrate.

Experimental set up

The set-up of kinetics of reduction experiment was illustrated in Figure 1 which consists of a vertical carborundum furnace, a computer monitor system for monitoring the weight change of the reacting sample and a temperature controller. The balance is on the top of furnace and is connected through a suspending thread. The kinetics experimental conditions were as follows: ilmenite concentrate 2 g; addition amount of coke (particle size 180-200 mesh) 15 mass%; ratio of adhesive of sodium silicate 5 mass%. The weighed ilmenite concentrate and coke were thoroughly mixed by stirring over 30 min. Pellets of ilmenite concentrate containing coke were dried at temperature of 500 °C for 6 h in a muffle furnace.

Measuring principles of microwave absorbing characteristics

The measuring principle and equipment referred to our preciously published paper, in which the method of microwave cavity perturbation and equipment has been described in detail [20].

Reduction degree of ilmenite concentrates

The weight loss of pellets containing coke during reduction process included: the evaporation of water, emission of volatiles in coke, reduction of Fe oxide and carbon gasification. According to the definition of basic reduction degree, the following equation could be obtained:

$$R = \frac{\Delta W_0}{M_0} \times 100\% =$$
$$= \frac{\Delta W_\Sigma - \Delta W_C - \Delta W_V - \Delta W_W}{M_0} \times 100\% \qquad (1)$$

where ΔW_0 is the removing amount of oxygen of iron oxides in ilmenite concentrates (g); M_0 is total amount of oxygen in ilmenite concentrates (g); ΔW_v is the emission amount of volatiles (g); ΔW_w is the emission amount of water (g); ΔW_Σ is the total weight loss amount (g); ΔW_c is the amount of carbon loss (g).

In order to eliminate the effects of release of volatile components and water on reduction degree, pellets of aluminum oxide powder containing coke were prepared using the same method as for pellets of ilmenite concentrates. The emission ratio of volatiles and water of pellets was calculated using the following equation:
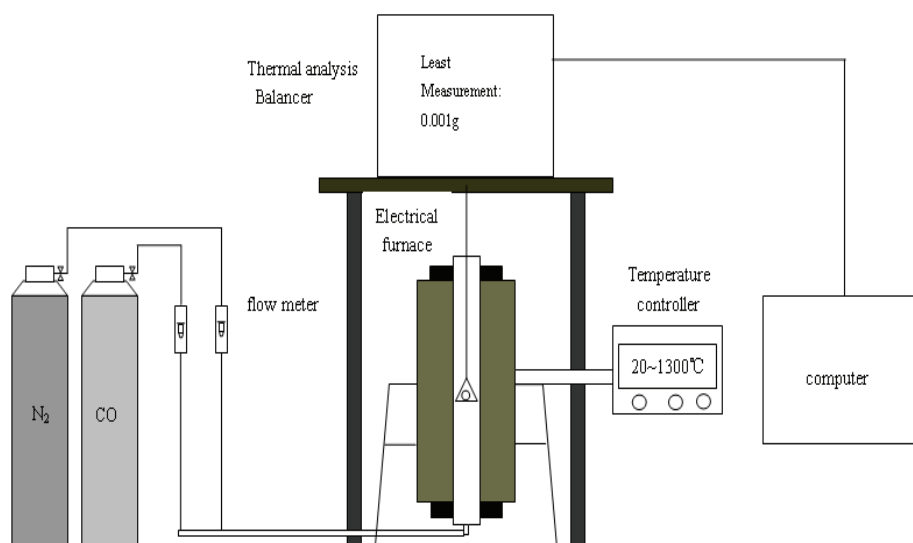

Figure 1. Schematic diagram of the reductive experimental setup.

$$f_{A-P} = 100 \frac{\Delta W_V + \Delta W_W}{W_{A-P}} \qquad (2)$$

where f_{A-P} is ratio of weight loss for pellets of aluminum oxide powder containing coke and W_{A-P} is the mass of pellets of aluminum oxide powder containing coke.

When replacing the mass of pellets of aluminum oxide powder containing coke by using pellets containing carbon (W), $W = W_{A-P}$, reduction degree was obtained as:

$$R = 100 \frac{\Delta W_\Sigma - \Delta W_C - f_{A-P} W}{M_0} \qquad (3)$$

Assuming the reaction process of the carbon reduction of iron oxides under the high temperature is:

$$Fe_x O_y + C = Fe_x O_{y-1} + CO \qquad (4)$$

equation:

$$\Delta W_C = \frac{12}{16} \Delta W_0$$

was obtained; so the calculating formula for reduction degree was deduced as:

$$R = 100 \frac{4(\Delta W_\Sigma - f_{A-P} W)}{7 M_0} \qquad (5)$$

For carbothermic reduction of ilmenite concentrates within the appropriate reduction temperature, only the reduction process of iron oxides occurs; the reduction process of TiO_2 to low-valence titanium will occur accompanying the reduction process only at a higher temperature. So, carbothermic reaction of ilmenite concentrates can be considered as:

$$Fe_x O_y \cdot TiO_2 + C = Fe_x O_{y-1} + CO + TiO_2 \qquad (6)$$
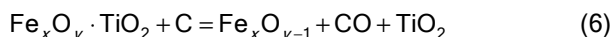
If controlling the appropriate temperature, assuming TiO_2 formed during the carbothermic reduction process of ilmenite concentrates is not reduced, the reduction degree for ilmenite concentrates can be simplified according to Eq. (5), where M_0 should be corrected, if M_{0r} is the ratio of O in $Fe_x O_y$:

$$M_{0r} = \frac{16 y}{16 y + 56 x} \qquad (7)$$

$$R = 100 \frac{64 y (\Delta W_\Sigma - f_{A-P} W)}{7(16 y + 56 x)} \qquad (8)$$

The oxygen amount of $Fe_x O_y \cdot TiO_2$ is:

$$M_0^\bullet = \frac{16 y}{16 y + 56 x + 112} \qquad (9)$$

At this point, the calculating equation for reduction degree for pellets of ilmenite concentrates containing carbon was finally obtained as:

$$R = 100 \frac{4(16 y + 56 x)(\Delta W_\Sigma - f_{A-P} W)}{7(16 y + 56 x + 112)} \qquad (10)$$

RESULTS AND DISCUSSION

Calibrations of weight-loss fraction of coke and ilmenite concentrates

It can be seen from Tables 1 and 2 that ilmenite and coke contain volatiles. The amount content of volatile, sulfur and water, especially for coke, is more than 6.02%. If this amount were calculated as weight of oxygen loss, it would lead to errors in calculation of reduction degree by using the method of weight loss. So, calibrations of weight loss fraction at different reduction temperatures by using coke as reduction agent were investigated, in order to increase the calculation accuracy of reduction degree of ilmenite concentrate.

Calibration conditions: coke mass 0.3 g, ilmenite concentrates 2 g, the others were the same as defined in "Experimental set up". The upper deck of coke and ilmenite concentrates were covered by Al_2O_3, which had been calcined to constant weight, in order to prevent coke injection and oxidation of ilmenite concentrates. Furthermore, the process was performed under a protective atmosphere of N_2, preventing weight loss of coke oxidation or weight gain of oxidation of ilmenite concentrates. Figures 2 and 3 show the relationship between reduction time and weight loss fraction of coke at different reduction temperatures and the relationship between reduction time and weight loss fraction of ilmenite at different reduction temperatures, respectively.

It can be found that the weight loss of both coke and ilmenite concentrates increases with increasing of temperature at the same heating time. Under the same constant temperature, weight loss of coke and ilmenite concentrates increases with increase in time and ilmenite concentrates, losing weight faster at early stage, while weight loss of volatiles is slower at final stage. Therefore, increasing constant temperature and heating time will enhance the weight loss of coke and ilmenite concentrates; if calibrations of weight-loss fraction of coke and ilmenite concentrates were not carried out, it would cause a large calculation error for the reduction degree.

The sum of weight losses of coke and ilmenite concentrates at different reduction temperature for carbothermic reduction of ilmenite concentrate were

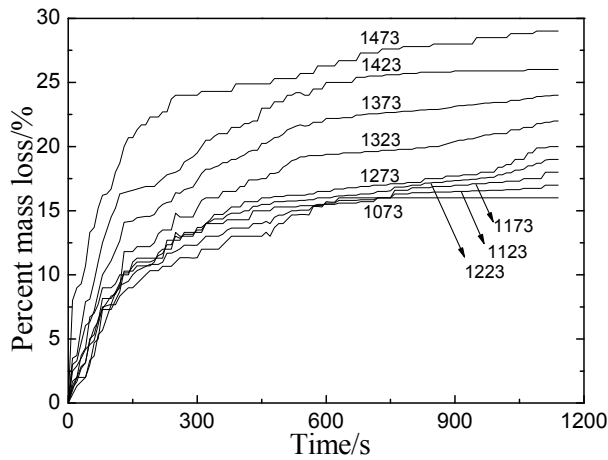obtained from Figures 2 and 3, and the results are listed in Table 3.

Figure 2. Relationship between reduction time and weight loss fraction of coke at different reduction temperatures.
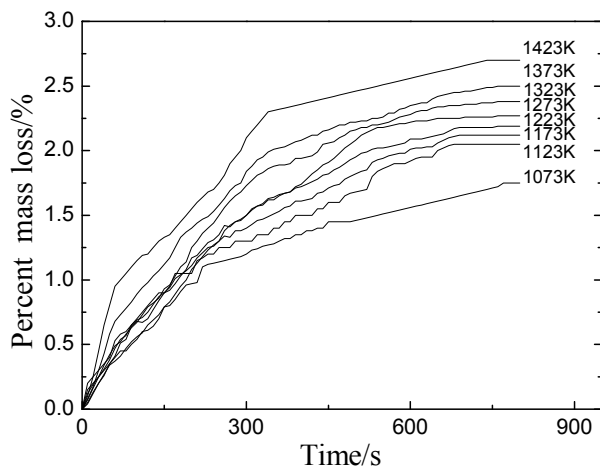

Figure 3. Relationship between reduction time and weight loss fraction of ilmenite at different reduction temperatures.

Carbothermic reduction of ilmenite concentrates catalyzed sodium silicate

Generally speaking, the larger the diameter of pellets (weight of pellets), the lower the performance of chemical reaction. If the diameter of pellets were small, it would cause the difficulty of follow-up sample characterization. The weight of pellets was investigated in the present study. The conditions were as follows: sodium silicate 3%; coke 15%, ilmenite concentrate 1-8 g (results shown in Figure 4); other set of conditions: sodium silicate 5%, others the same as defined in "Experimental set up" (results shown in Figure 5).
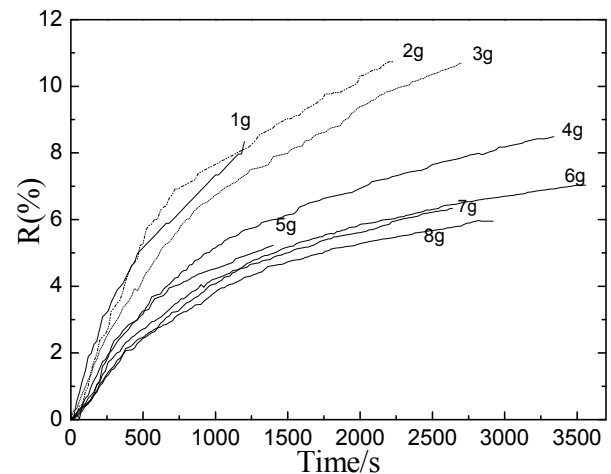

Figure 4. Relationships between reduction degree and different ball weights at 1050 °C.

It can be seen from Figure 4 that the reaction rate and weight loss for pellets of 2 g are the highest, the maximum reduction degree is 10.73%, so the weight of pellet was chosen to be 2 g. From Figure 5 it can be seen that the reduction rate becomes faster at temperatures above 1423 K, the reduction degree is 22.74%, being larger compared to that in Figure 4 at the same conditions, while the corresponding amount of sodium silicate has increased only 2%, indicating that sodium silicate has a catalytic effect on the reduction process.

If nuclei formation and growth are the controlling steps during the carbothermic reduction of ilmenite concentrates, the rate expression can be given by

Table 3. Total weight loss of pellets; coke, 0.30 g; ilmenite concentrate, 2.00 g

Temperature, °C	Weight loss of coke, g	Weight loss of ilmenite concentrate, g	Total weight loss, g
800	0.048	0.035	0.083
850	0.052	0.041	0.093
900	0.054	0.042	0.096
950	0.057	0.043	0.10
1000	0.060	0.045	0.105
1050	0.066	0.048	0.114
1100	0.072	0.05	0.122
1150	0.078	0.054	0.132

Avrami-Erofeev Equation [36-38], which is one of the equations often used to describe the nucleation kinetics and subsequent crystal growth:

$$(-\ln(1-\alpha)^{\frac{1}{n}}) = kt \quad \text{or} \quad \alpha = 1 - \exp(-kt^n) \tag{11}$$

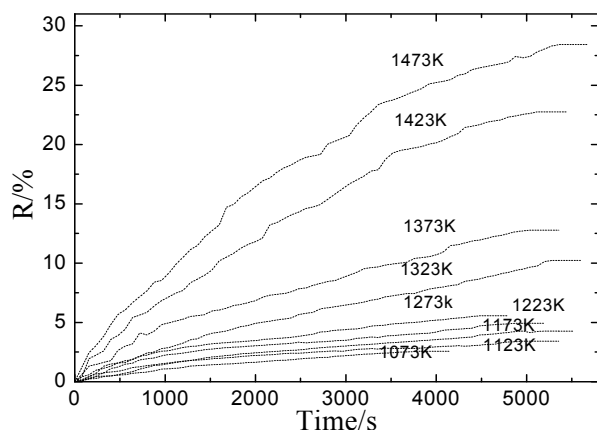where α is conversion value, n the reaction order, k the rate constant and t the time.

Figure 5. Relationships between reduction degree and reduction time.

Rate equation described by the oxygen weight loss of reactants of $TiO_2 \cdot Fe_xO_y$ (assumed random nucleation and its subsequent growth, $n = 1$) could be obtained as:

$$\ln(1-\alpha) = -kt \tag{12}$$

where k is the reaction rate (1/min); α is the oxygen weight loss of reactants of $TiO_2 \cdot Fe_xO_y$, being the reduction degree of pellets containing carbon (%); t is reduction time (min).

Making a plot by using the equation above and reduction degree data in Figure 5, reaction rate constants at different constant temperatures can be obtained (Table 4), and by making a plot of ln K vs. 1/T. Figures 6 and 7 can be obtained. It can be found from

Table 4 that multiples of reaction rate increase from 4.43 to 9.0 rapidly, reaching stabilization at temperature of 1473 K.

The linear equation $y = -4.3841x - 8.0708$ is obtained by fitting the data in Figure 6. The initial apparent activation energy for reduction of ilmenite concentrates catalyzed by $Na_2SiO_3 \cdot 9H_2O$ was 36.45 kJ/mol; the pre-exponential factor was $60e^{-8.0708}$ min^{-1}. By fitting Figure 7, the linear equation $y = -16.254x + 1.3425$ was also obtained. The initial apparent activation energy for reduction of ilmenite concentrates catalyzed by $Na_2SiO_3 \cdot 9H_2O$ was 135.14 kJ/mol; the pre-exponential factor was $60e^{-1.3425}$ min^{-1}.
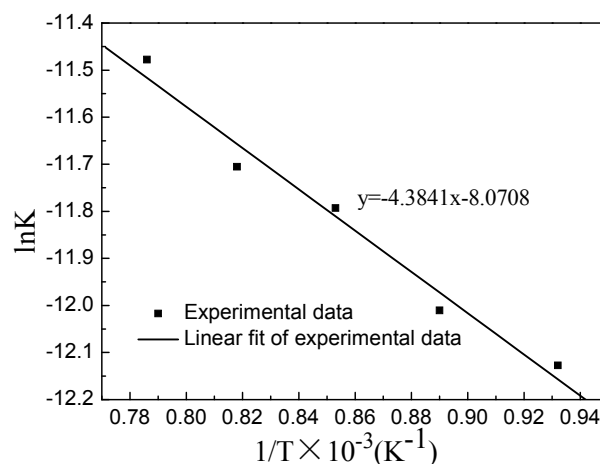

Figure 6. Plot of ln K vs. 1/T (1023-1273 K range).

The TG and DSC curves of $Na_2SiO_3 \cdot 9H_2O$ were used to confirm its catalytic effect for carbothermic reduction process of ilmenite concentrates.

It can be seen from TG curves of sodium silicate in Figure 8 that the temperature range of 348.5-494.3 K is attributed to the weight loss of crystallization water, of which the weight loss ratio being bigger more than 50%, losing almost all crystallization water, and appears as an endothermic peak in DSC curves shown in Figure 9. The melting point of sodium silicate is 1326 K, indicating that melting endothermic

Table 4. Reduction temperature and corresponding reaction rate constant

Temperature, K	Reaction rate constant, 10^{-6} min^{-1}	Reaction rate multiplier
1073	5.41	1.00
1123	6.08	1.12
1173	7.51	1.39
1223	8.25	1.52
1273	10.36	1.91
1323	18.47	3.41
1373	23.96	4.43
1423	48.70	9.00
1473	58.50	10.81

reaction for sodium silicate occurs, prompting the enhancement of activation of alkali metal of sodium ions, which are absorbed by coke, prompting the reaction of carbon gasification, in agreement with the great changes of reaction rate constant in the temperature range of 1373-1423 K.
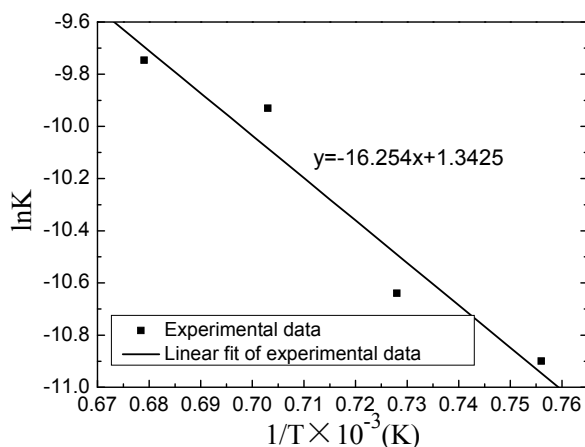

Figure 7. Plot of ln K vs. 1/T (1323-1473 K range).

Changes of microwave-absorbing characteristics and XRD characterization

Figure 10 shows the microwave spectra of reduction products of ilmenite concentrates catalyzed by sodium silicate, and Table 5 lists the correspondence microwave absorbing characteristics parameters. Relative frequency shift, attenuations and quality factors (Q) at the first wave crest of microwave

spectra were computed by computer software. From these parameters, the microwave-absorbing characteristics of reduction products at different conditions were compared (Figures 11 and 12).

Through analyses of microwave-absorbing characteristics such as attenuation voltage, frequency, bandwidth and quality factor, combined with Table 5 and Figures 10-12, it can be concluded that there are great changes for microwave-absorbing characteristics of reduction products obtained at temperatures of 900 and 1100 °C. In order to confirm the changes for microwave-absorbing characteristics, reduction products obtained at temperatures of 900, 1100 and 1150 °C were also characterized by XRD (Figures 13 and 14).

It can be seen from Figure 13 that the phases of reduction products at 1100 °C are $FeTiO_3$ (artificial ilmenite), iron and salts of silicate and very small amount of Fe_3O_4. A characteristic peak of Fe at 44.68° is 683 cps, showing that the formation of Fe accumulates, and reduction reaction reaches to some extent. The $FeTiO_3$ phase indicates that sodium silicate catalytic reaction is not complete. The Fe_3O_4 phase shows that mechanism of reduction reaction of ilmenite concentrates catalyzed by sodium silicate is similar to that of common iron ore.

It is shown that the intensity of characteristic peak of Fe at 44.68° is 176, 683 and 933 cps from low temperature to high temperature, indicating that the intensity of Fe increases with increasing temperature, resulting in the increase of iron content (under the
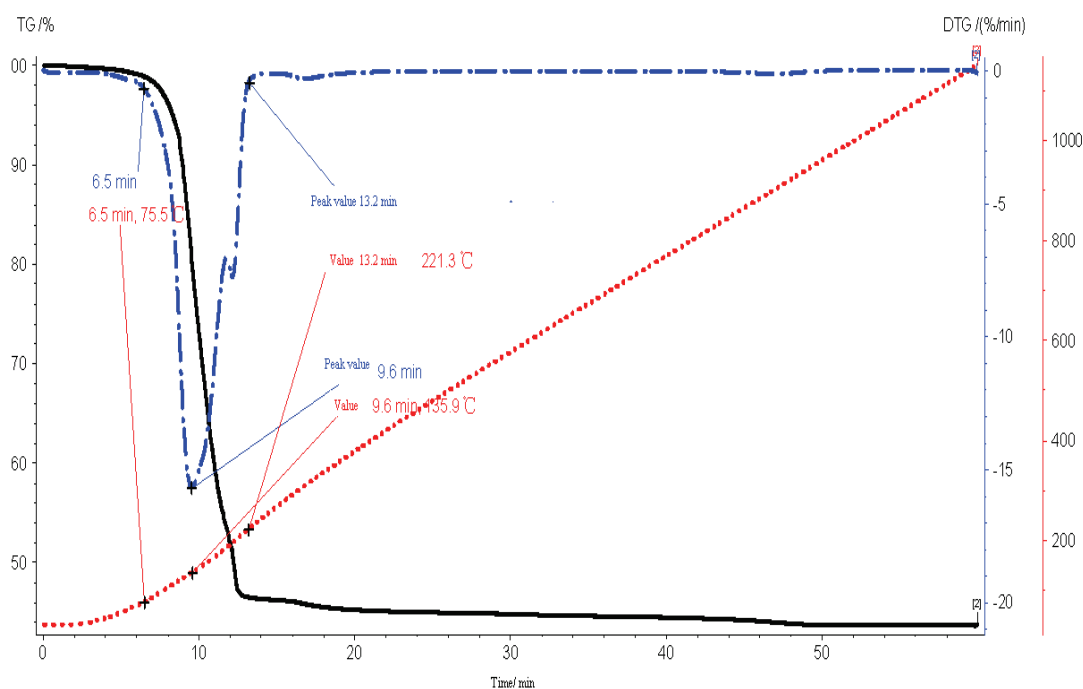

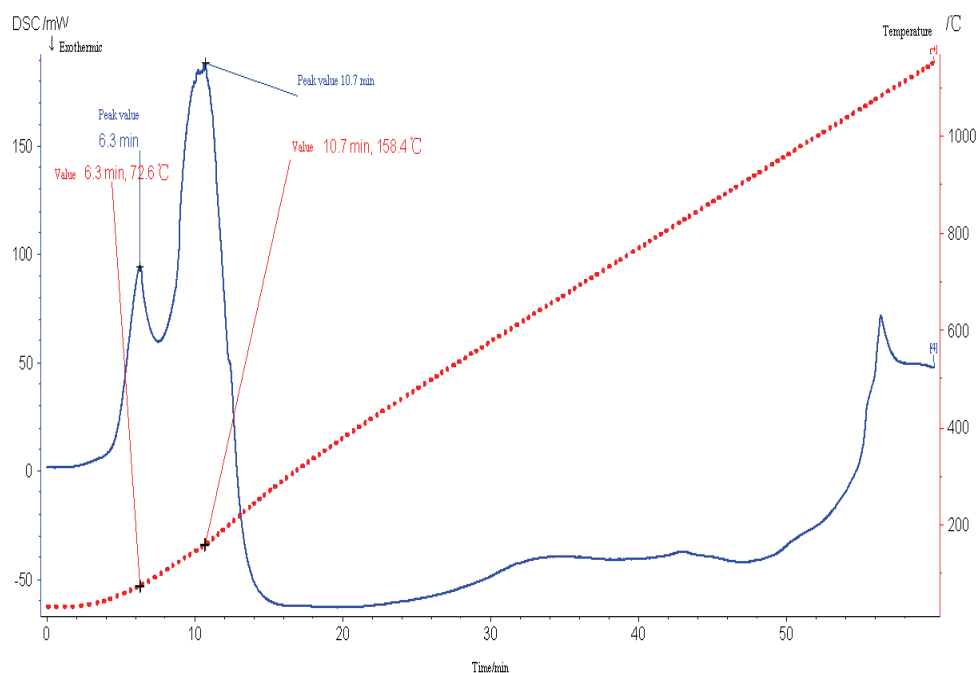*Figure 8. TG Curves of sodium silicate.*
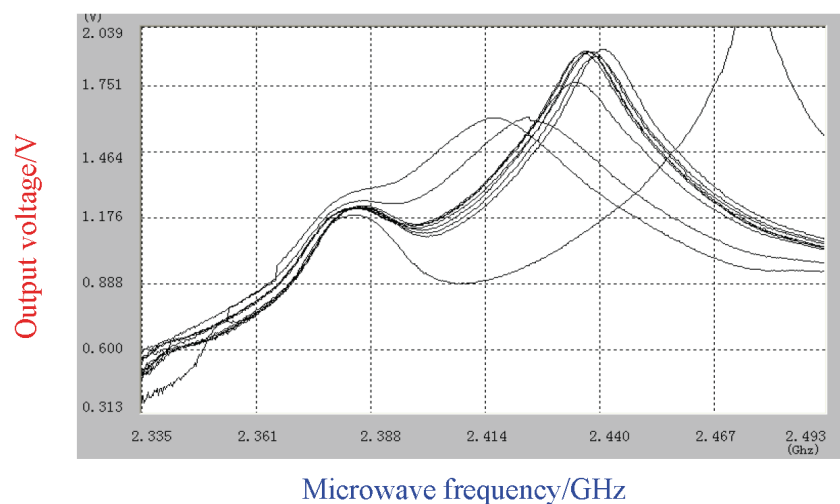
Figure 9. DSC Curves of sodium silicate.

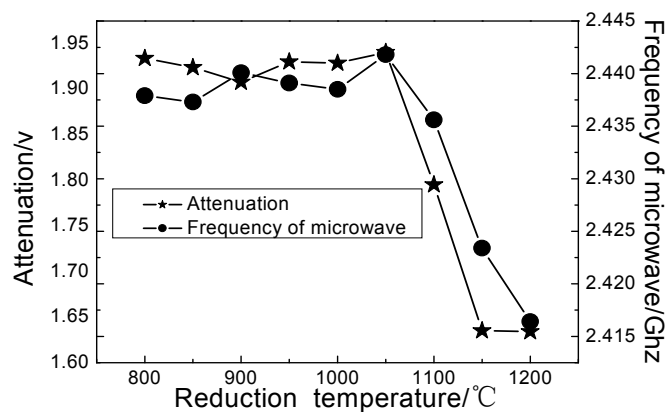*Figure 10. Microwave spectra of reduction products.*

Figure 11. Relationships between reduction temperature and attenuation, frequency of microwave.
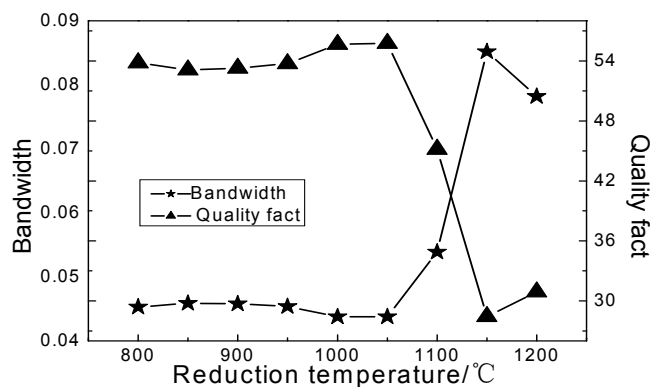
Figure 12. Relationships between reduction temperature and bandwidth, quality factor.

Table 5. Microwave-absorbing characteristic parameters of reduction products

| Product	Attenuation voltage, V	Frequency, GHz	Bandwidth, GHz	Quality factor (Q)
Empty cavity	2.2135	2.4755	0.0320	77.36
NZ_{800}	1.9342	2.4379	0.0453	53.82
NZ_{850}	1.9241	2.4373	0.0459	53.10
NZ_{900}	1.9081	2.4401	0.0458	53.28
NZ_{950}	1.9303	2.4391	0.0454	53.72
NZ_{1000}	1.9288	2.4385	0.0438	55.67
NZ_{1050}	1.9406	2.4418	0.0438	55.75
NZ_{1100}	1.7955	2.4356	0.0539	45.18
NZ_{1150}	1.6351	2.4234	0.0852	28.44
NZ_{1200}	1.6341	2.4164	0.0782	30.90
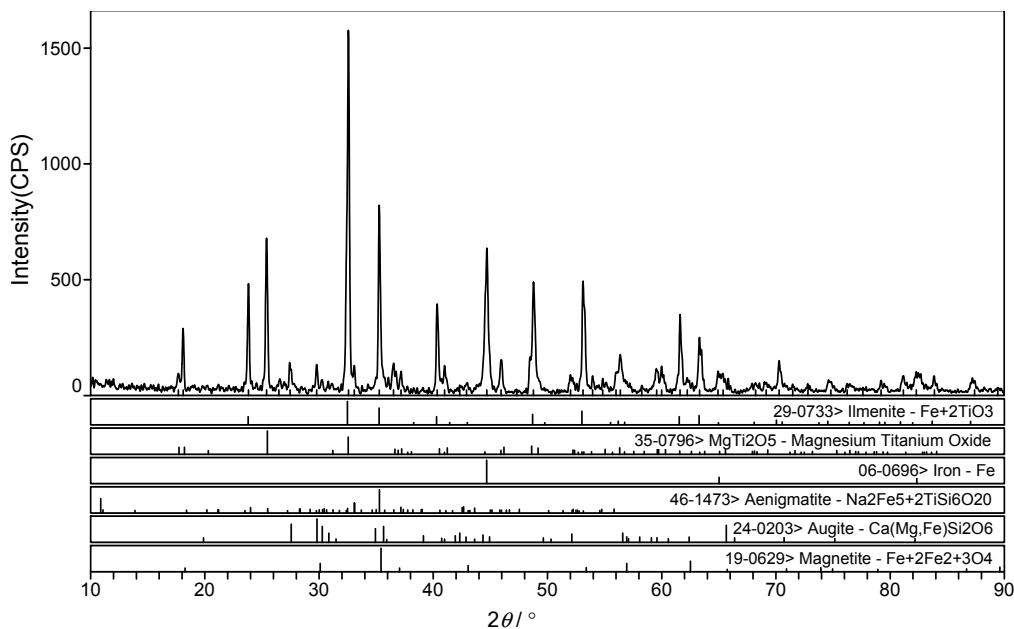
Figure 13. XRD Pattern of reductive product at 1100 °C.
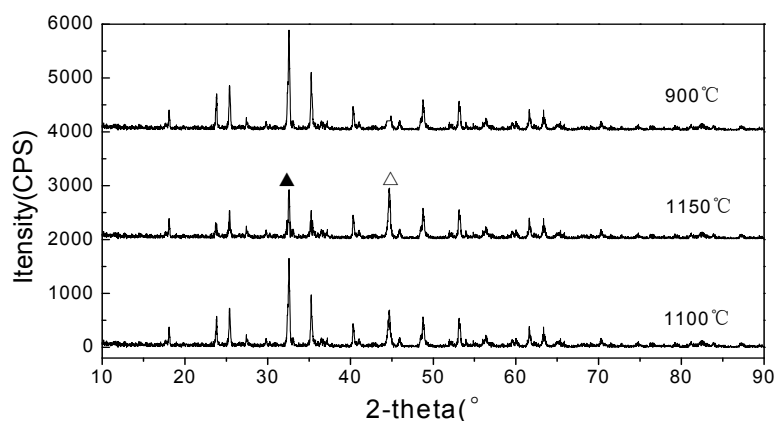
Figure 14. XRD Patterns of reductive product at different reduction temperatures ($\triangle$: FeTiO$_3$, $\blacktriangle$: Fe).

same measuring conditions). The intensity of the reduction product at temperature of 900 °C is low, which can be considered the initial formation of Fe, demonstrating that the reduction reaction of ilmenite concentrates catalyzed by sodium silicate starts at temperature of 900 °C. The intensity of characteristic peak of FeTiO$_3$ at 32.58° is 1859, 1652 and 908 cps from low temperature to high temperature, showing that the content of FeTiO$_3$ decreases with increasing reaction temperature, however, even though the temperature reaches 1150 °C, the reduction reaction of ilmenite concentrates is not complete. The sharp change of intensity becomes small at temperature range of 1100 to 1150 °C, indicating that reaction rate of carbothermic reduction of ilmenite concentrates becomes faster, which agrees with the results of multiples of rate increasing from 4.43 to 9.0 listed in Table 4. Therefore, the formation of reduction production iron and Fe accumulation and the decrease of content of ilmenite concentrates are the main reasons for the large changes of microwave-absorbing characteristics of reduction products.

CONCLUSIONS

The reduction degree of ilmenite concentrates reduction reaction has been deduced as $R = 4/7(16y + 56x)(\Delta W_\Sigma - f_{A-P}W)/(16y + 56x + 112)$ from reduction degree expression $R = 100\Delta W_0/M_0$.

Kinetics experimental results show that activation energies of initial and later stage are 36.45 and 135.14 kJ/mol, respectively. There is a great change for reduction rate at temperatures of 1100 and 1150 °C; the catalysis effect and great change for reduction rate were evaluated by TG and DSC curves of sodium silicate.

Microwave-absorbing characteristics of reduction products were measured by the method of microwave cavity perturbation. It was found that mic-

rowave absorbing characteristics of reduction products obtained at temperatures of 900, 1100 and 1150 °C have significant differences. XRD characterization results explained the formation and accumulation of reduction product Fe, and pronounced changes of microwave absorbing characteristics due to the decrease of the content of ilmenite concentrates.

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NAUČNI RAD

KINETIKA KARBOTERMALNE REDUKCIJE KONCENTRATA ILMENITA KATALIZOVANE NATRIJUM-SILIKATOM I MIKROTALASNO--APSORPCIONE KARAKTERISTIKE PROIZVODA REDUKCIJE

U ovom radu je ispotivana kinetika karbotermalne redukcije koncentrata ilmenita katalizovane natrijum-silikatom. Stepen redukcije koncentrata ilmenita je određen kao R = = 4/7(16y + 56x)(ΔWΣ - f$_{A-P}$W)/(16y + 56x + 112). Rezultati pokazuju da su vrednosti energije aktivacije početne i krajnje faze 36,45 i 135,14 kJ/mol, redom. Na temperaturama od 1100 i 1150 °C primećena je velika promena u brzini redukcije. Uticaj katalize i velika promena brzine redukcije je određena pomoću TG i DSC krive natrijum-silikata. Mikro-talasno-apsorpcione karakteristike proizvoda redukcije su merene metodom mikrotalasnih kavitacionih perturbacija. Ustanovljeno je da se mikrotalasne apsorpcione karakteristike proizvoda redukcije dobijenih na temperaturama 900, 1100 i 1150 °C jako menjaju i u kombinaciji sa XRD objašnjavaju stvaranje i akumulaciju proizvoda redukcije Fe. Velike promene mikrotalasnih apsorpcionih karakteristika se javljaju i zbog smanjenja sadržaja koncentrata ilmenita.

Ključne reči: natrijum-silikat; koncentrati ilmenita; katalitička redukcija; kinetika; mikrotalasne apsorpcione karateristike.