

HIGH EFFICIENCY EXTRACTIONS OF V, Cr, Ti, Fe, AND Mn FROM VANADIUM SLAG BY MICROWAVE HEATING

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Abstract

The vanadium slag (V-slag) is generated from smelting vanadium titanomagnetite ore, which contains valuable elements, such as V, Ti, Cr, Fe, and Mn. The traditional methods were mainly focused on the extractions of V and Cr by oxidation or reduction processes. In the present work, chlorination method was adopted to keep the valence state of each element in original state. In order to speed up the diffusion of elements and reduce volatility of molten salt, microwave heating was examined in the current paper. The results indicated that it only took 30 min to chlorinate V-slag at 800 °C, and the chlorination ratios of V, Cr, Mn, Fe, and Ti reached to 82.67%, 75.82%, 92.96%, 91.66%, and 63.14%, respectively. Compared with the results by conventional heating for 8 h, this extraction rate by microwave heating showed greater advantages. In addition, microwave heating effectively reduced volatilization of AlCl₃ by shortening the reaction time. The volatilization ratio of AlCl₃ in this microwave heating was 3.92% instead of 8.97% in conventional heating (1h). The mechanism of efficient chlorination can be summarized as the enhancement of ions diffusion process and enhanced chemical reaction due to local high temperature.

Keywords: Vanadium slag; Microwave heating; Molten salt; High efficiency chlorination

1. Introduction

Vanadium is a very important metal element widely used in steel, catalyst, and aerospace industry [1]. Vanadium can be extracted from V-slag. A large amount of V-slag can be obtained from vanadium-containing molten iron by converter process. With the increase of global vanadium product, production of V-slag in China was about 400,000 tons in 2013 [2].

The V-slag contains a large amount of valuable metals, such as V, Cr, Mn, Fe, and Ti. The traditional method for extracting valuable metals in V-slag mainly include oxidation, reduction, and molten salt chlorination [3-9]. The oxidation methods mainly imply that V³⁺ is oxidized to V⁵⁺, and Cr³⁺ converts to Cr⁶⁺ [3-6]. In reduction process, the pulverized V-slag is reduced by carbon in molten iron to form a vanadium-iron alloy [8]. V and Cr in V-slag can be utilized by oxidation and reduction method, while the molten salt chlorination process [10] can simultaneously recover V, Cr, Mn, Fe, and Ti from V-slag [9]. V, Cr, Mn, Fe, and Ti in V-slag are chlorinated to water-soluble chlorides of the original

valence metal ions at 900 °C for 8 h. The molten salt chlorination method has its limitations, such as high volatilization of anhydrous AlCl₃ [11], long chlorination time, and high energy consumption. Thus, a new method for molten salt chlorinating V-slag, which was highly efficient and energy-saving, should be developed.

The advantages of microwave heating include rapid heating [12], selective heating [13], instant heating [12], and non-thermal effect [14]. Microwave heating can save energy [12], shorten processing time [15], reduce the temperature [16, 17], and catalyze reaction [18]. Microwave heating technology is widely used in biology, chemistry, materials, and metallurgy. In the microwave field, microwave selective heating of different microwave absorption capacity mineral components resulted in thermal stress cracking [19-21]. Microwave can improve the surface properties of materials, which reduce the molten salt synthesis temperature and shorten the time [16, 17]. The microwave roasting can alter the spinel structure of the V-slag, enhance the reactivity of the V-slag, and decrease sensitivity to temperature of the V

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leaching from the V-slag [22].

The purpose of this paper was to chlorinate V-slag with microwave heating. Effects of chlorination temperature and time on microwave heating chlorination V-slag were investigated. The results of microwave heating chlorination V-slag were compared with conventional heating. In addition, the mechanisms of strengthening chlorination V-slag by microwave field were explained.

2. Experimental Methods

2.1. Raw Materials

The V-slag was provided by PanGang Group Co., LTD in Panzhihua, China. All the samples were crushed, milled, and screened with particle size < 0.074 mm. V-slag was dried at 105 °C for 4 h. XRD pattern of V-slag is shown in Figure 1, the main crystalline phases of the V-slag were vuorelainenite ((Mn,Fe)(V,Cr)₂O₄), fayalite, manganooan ((Fe,Mn)₂SiO₄), and titanomagnetite (Fe_{2.5}Ti_{0.5}O₄). The composition of V-slag was determined by inductively couple plasma optical emission spectroscopy (ICP-OES), which is shown in Table 1.

Analytically pure Anhydrous AlCl₃ (99%), NaCl (99.5%), and KCl (99.5%) were purchased at China National Pharmaceutical Group Corporation used in this work.

2.2. Procedures and Instrumentation

2.2.1. Sensitivity of raw materials to microwave heating

The vertical microwave furnace was provided by China Tangshan Microwave Nayuan Co., Ltd. The frequency of the microwave furnace was 2.45 GHz,

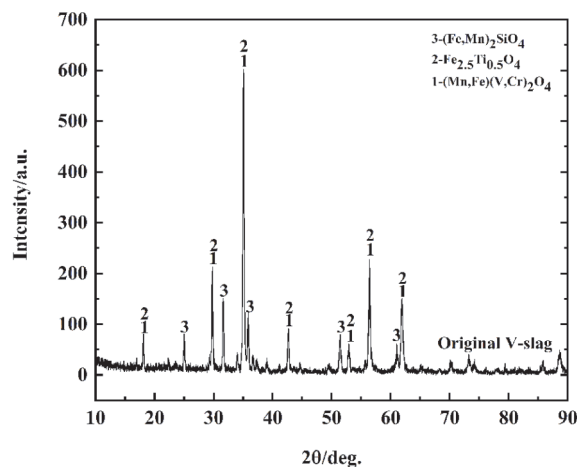


Figure 1. XRD pattern of original V-slag

Table 1. Chemical composition of the V-slag in wt%

Composition	V ₂ O ₃	Cr ₂ O ₃	MnO	FeO	TiO ₂	SiO ₂	Al ₂ O ₃	MgO	CaO
Content (%)	9.17	1.78	5.20	37.69	10.40	21.23	7.40	3.47	3.60

and its power could be adjusted between 0 and 4000 W. The structure is shown in Figure 2. 10 g V-slag, 10 g V-slag and 15 g AlCl₃, and 10 g V-slag and 40 g AlCl₃-(NaCl-KCl) mixture samples were placed in a quartz crucible, respectively. Then samples were put in the middle position of the microwave furnace with insulation material (no microwave absorption capacity). K-type thermocouple wrapped in stainless steel was inserted into the center of the sample to measure the temperature with a precision of ±5 °C. In the experiment, the argon (99.9%) was used as a protective gas. At a given microwave power of 2000 W, the temperature of sample rose to 800 °C after a period of time. After turning off the microwave, the product was obtained and cooled to room temperature in air.

2.2.2. Chlorination V-slag by microwave heating

In microwave heating chlorination V-slag process, 10g of V-slag was used in each experiment. The mass ratios of AlCl₃/V-slag and (NaCl-KCl)/AlCl₃ were 1.5:1 and 1.66:1, respectively. The sample was hold for a varied duration (10–60 min) once the temperature reached the desired value. The products of the experiment were immersed in 500 mL of deionized water for 1 h. Then, the products were separated by a suction filter. The experiment was repeated three times and the average value was reported. The chlorination ratio of V, Cr, Mn, and Fe was calculated by Equation 1, and the volatilization ratio of Ti was calculated by Equation 2:

$$\rho_{(V,Cr,Mn,Fe)} = \frac{c_{(V,Cr,Mn,Fe)} \times V}{M_{(V,Cr,Mn,Fe)}} \times 100\% \quad (1)$$

Where $\rho_{(V,Cr,Mn,Fe)}$ was the chlorination ratio of each element (V, Cr, Mn, and Fe) of V-slag, $c_{(V,Cr,Mn,Fe)}$ was the concentration of valuable metals (V, Cr, Mn, and Fe) in the liquid phase products measured by ICP-OES, V was the volume of deionized water, and $M_{(V,Cr,Mn,Fe)}$ was the initial content of valuable metals (V, Cr,

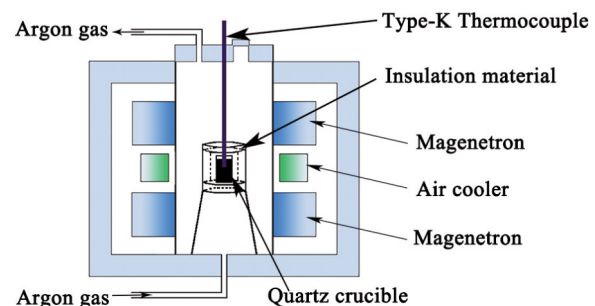


Figure 2. Microwave instrument structure schematic

Mn and Fe) in V-slag.

$$\rho_{Ti} = \left(1 - \frac{m_{Ti}}{M_{Ti}}\right) \times 100\% \quad (2)$$

where ρ_{Ti} was the volatilization ratio of Ti, m_{Ti} was the Ti content in solid product, and M_{Ti} was the initial content of Ti in V-slag.

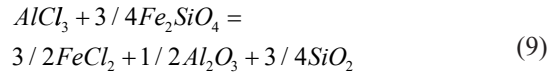
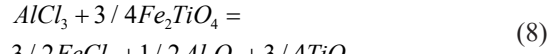
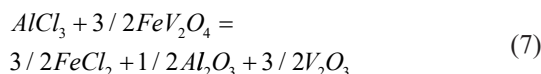
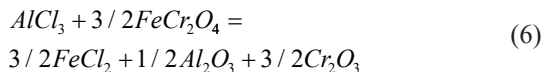
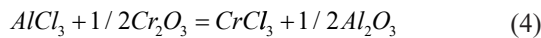
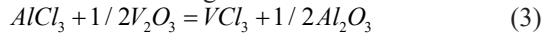
2.2.3. Characterization of the microwave heating chlorination V-slag

The patterns of chlorinated V-slag were measured by XRD (Rigaku TTRIII, Rigaku, Japan). ICP-OES (Varian715-ES, Varian, USA) was used to analyze the concentration of Fe, Mn, V, Cr, and Al in chlorinated products. XRF (AxiosMAX, Axios, Netherlands) was used to analyze concentrations of valuable metals remaining in chlorination products. The morphology of the chlorination products were analyzed by SEM (Quanta250, FEI, Netherlands).

3. Thermodynamics Chlorination V-slag by AlCl₃

The main crystalline phases of V-slag were FeCr₂O₄, FeV₂O₄, Fe₂SiO₄, and Fe₂TiO₄. The thermodynamic equations for the reactions of V-slag with AlCl₃ were shown in Equations 3-10. The FactSage 7.0 program was used to calculate the standard Gibbs free energies for these reactions. The results at different temperature are presented in Figure 3.

The standard Gibbs free energy of reactions 3-10 was negative at 300 °C-900 °C, indicating that the chemical reaction could happen. According to the relevant nature of Gibbs free energy, the smaller standard Gibbs free energy value of the equation, the easier the reaction will occur. The standard Gibbs free energies at the same temperature was $\Delta G^{\theta}(V_2O_3) > \Delta G^{\theta}(Cr_2O_3) > \Delta G^{\theta}(FeCr_2O_4) > \Delta G^{\theta}(FeV_2O_4) > \Delta G^{\theta}(Fe_2TiO_4) > \Delta G^{\theta}(Fe_2SiO_4) > \Delta G^{\theta}(MnO)$. Thus, chlorination of Fe₂SiO₄ was easier than chlorination of FeV₂O₄ and Fe₂TiO₄. After Fe₂SiO₄, FeV₂O₄, Fe₂TiO₄, and MnO chlorination, Cr₂O₃, TiO₂, and V₂O₃ reacted with AlCl₃. Therefore, thermodynamic calculations showed that AlCl₃ chlorination V-slag could be used in a range of 300 °C - 900 °C.



4. Results and Discussions

4.1. Microwave heating performance of molten salt chlorination V-slag

At a given microwave power of 2000 W, microwave heating temperature characteristic curve of V-slag, V-slag-AlCl₃ mixture, and V-slag-(NaCl-KCl)-AlCl₃ mixture are shown in Figure 4.

The microwave absorbing performance of material depends on the nature of the composition and structure [23], which can be evaluated by the temperature characteristic curve. The average

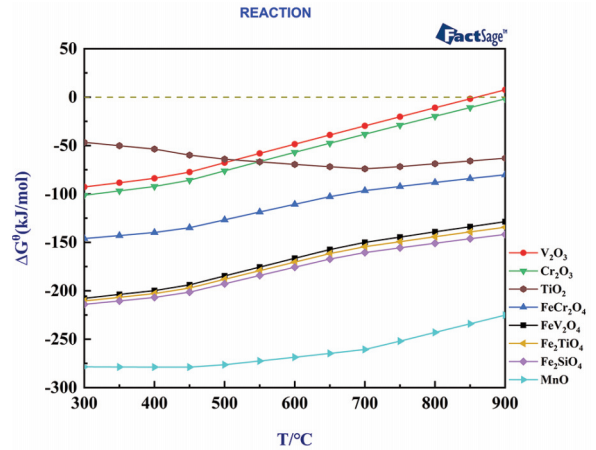


Figure 3. Plots of standard Gibbs free energies as a function of temperature in Equations 3-10 (normalized by 1mol AlCl₃)

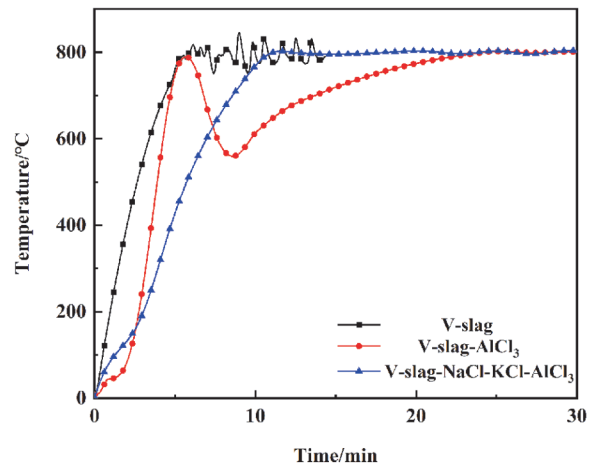


Figure 4. Microwave heating temperature characteristic curve of V-slag; V-slag-AlCl₃ mixture; V-slag-(NaCl-KCl)-AlCl₃ mixture



heating rate of V-slag reached up to 134 °C/min and temperature of 800 °C was achieved within 6 min. The average heating rate of V-slag-AlCl₃ mixture reached up to 120 °C/min and temperature of 800 °C was achieved within 7 min. The curve shows that the average heating rate of V-slag-(NaCl-KCl)-AlCl₃ mixture reached up to 67 °C/min and heating for 12 min to reach 800 °C. The microwave absorbing capacity was V-slag > V-slag-AlCl₃ mixture > V-slag-NaCl-KCl-AlCl₃ mixture. The spinel and olivine phases in the V-slag had a face-centered cubic octahedral defects structure [24]. Structural defects could cause materials to absorb microwave [25]. In addition, titanomagnetite had good microwave absorption capacity. For V-slag, the rapid rise of temperature was mainly ascribed to the presence of the titanomagnetite, spinel, and olivine.

In the V-slag temperature characteristic curve, it was shown that the temperature started to appear unstable after 6 min at 800 °C. The difference between highest temperature and lowest temperature approximately reached 80 °C. It was attributed to the good microwave absorption capacity of V-slag, which led the temperature to rise too fast. In the curve of V-slag-AlCl₃ mixture, temperature started to decrease after rising to 800 °C. Compared with the curve of V-slag-AlCl₃ mixture, the heat preservation process of V-slag-(NaCl-KCl)-AlCl₃ mixture curve was relatively stable. The result indicated that the molten salt had a positive effect on the stabilizing sample temperature. Furthermore, molten salt have great potential as thermal energy storage [26]. Introducing a molten salt medium into the microwave heating chlorination V-slag can stabilize the chlorination temperature and provide a liquid phase reaction environment.

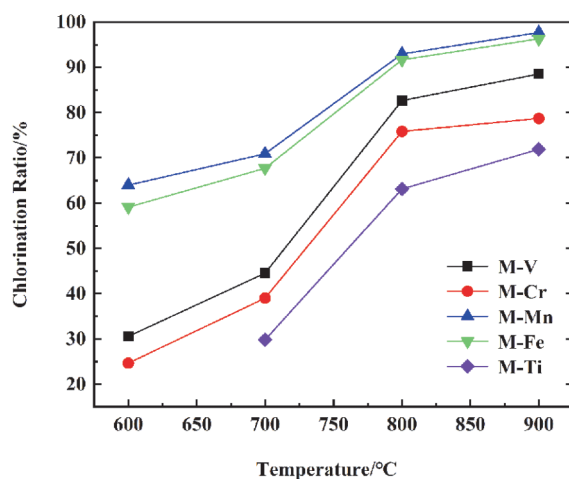


Figure 5. Effect of temperature on chlorination of valuable metals V, Cr, Mn, Fe, and Ti from microwave chlorinate V-slag for 30 min

4.2. Effect of temperature on chlorination ratio

In this work, V-slag-(NaCl-KCl)-AlCl₃ mixture sample was kept at 600 °C - 900 °C for 30 min. Effect of temperature on chlorination of valuable metals in V-slag by microwave heating (M) was shown in Figure 5.

It can be found that the chlorination ratios of valuable metals V, Cr, Mn, Fe, and Ti from V-slag increased significantly with temperature. At 600 °C, the chlorination ratios of V and Cr were only 30.55% and 24.65%, respectively. The chlorination ratios of valuable metals V, Cr, Mn, Fe, and Ti for microwave heating chlorination V-slag rose to 82.67%, 75.82%, 92.96%, 91.66%, and 63.14% at 800 °C. When the sample was heated by microwave to 800 °C - 900 °C, the chlorination ratio gradually reached a steady state. The XRD pattern (Figure 6) showed that product at 600 °C contained vuorelainenite, titanomagnetite, fayalite, and manganooxide peak. In addition, microwave heating decreased the intensity of the vuorelainenite, titanomagnetite, fayalite, and manganooxide peak, suggesting that AlCl₃ started to react with V-slag. In Figure 7(a), the void was observed at the phase interface of the spinel (1) and the olivine (2), and the olivine phase (2) was covered by the flocs. The EDS showed that the composition of flocs was Al-Si-O. The chlorination ratios of Fe and Mn were higher than V and Cr at 600 °C, which indicated that AlCl₃ firstly reacted with the olivine phase (2). Figure 5 shows that the chlorination ratio of valuable metals at 700 °C was relatively low. It was observed that the Ca(Fe,Mn)Si₂O₆ in Figure 6 still existed at 700 °C, leading to the relative low chlorination ratio of Fe and Mn. Figure 7(b) shows the SEM morphologies of chlorination product heated to 700 °C for 30 min. The spinel phase (1) and the olivine phase (2) were almost completely wrapped by the flocs, which indicated that

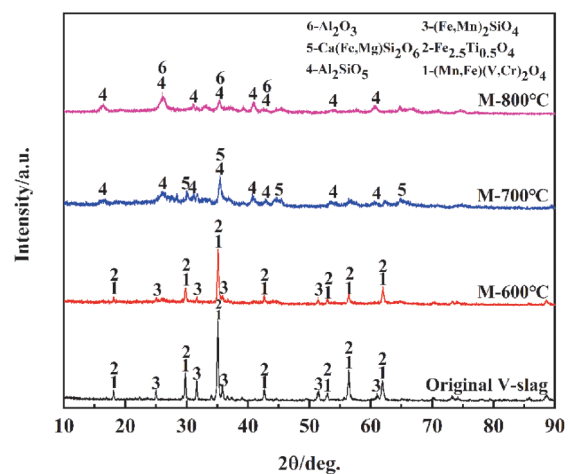


Figure 6. XRD patterns of product at different chlorination temperature (product washed with deionized water)

the chlorination ratio of valuable metals was relatively low. The Figure 6 suggested that $\text{Ca(Fe,Mn)Si}_2\text{O}_6$ disappeared at 800 °C, which explained that the chlorination ratio of Fe and Mn reached 91.8% and 92.4%, respectively. As shown in Figure 7(c), the morphology of spinel and olivine disappeared in the SEM map, and the residual elements in the surface scan were diffusely distributed. The SEM measurements indicated that V-slag could almost be completely chlorinated by the microwave heating method at 800 °C after 30 min, which coincided with the ICP-OES measurement results.

4.3. Effect of holding time on chlorination ratio

The effect of holding time (10 to 60 min) on chlorination of valuable metals Fe, Mn, V, and Cr in V-slag was investigated at 800 °C.

As shown in Figure 8, the chlorination ratio of Fe and Mn reached 80% within 10 min, while the chlorination ratio of V and Cr reached 75% after 30

min. Thus, chlorination ratio of V and Cr was more sensitive to holding time than Fe, Mn. The chlorination ratio of V and Cr increased by 30% in 20 min. The chlorination ratio of Fe after treatment for 30 min was 91.66% while it reduced to 89.05% with increasing treatment time to 60 min. The chlorination ratio of Cr had the same change as Fe, which could be related to the volatilization of chloride. The vapor pressures of FeCl_2 , MnCl_2 , VCl_3 , and CrCl_3 at various temperature were calculated by Factsage software. The evaporation of FeCl_2 , CrCl_3 , and VCl_3 with positive vapor pressure was more serious than MnCl_2 . The decrease of the chlorination ratio for Fe and Cr during the experiment.

In this paper, the V-slag-(NaCl-KCl)- AlCl_3 mixture sample volatilization at 800 °C for 10 to 60 min was investigated. The volatilization ratio of the sample gradually increased with the chlorination time. The volatilization ratio of the sample after 30 min was 1.96% while it increased to 4.34% with increasing time to 60 min. Thus, the optimal chlorination time was 30 min.

4.4. Comparison of traditional heating and microwave heating

Compared with chlorination ratio of valuable metals in V-slag by microwave and conventional heating at 800 °C, the results are shown in Table 2.

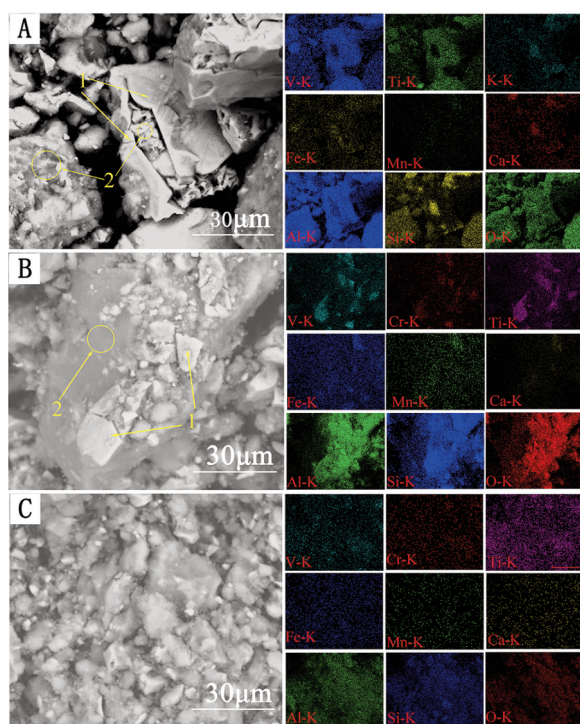


Figure 7. SEM morphologies of products at (a) 600 °C, (b) 700 °C, and (c) 800 °C for 30 min by microwave heating (products washed with deionized water)

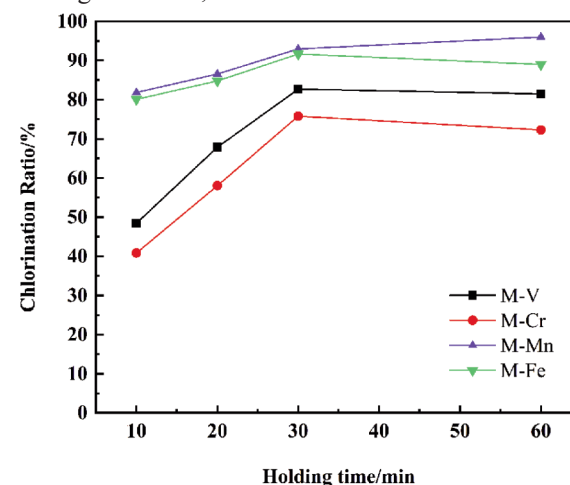


Figure 8. Effect of holding time on chlorination ratio of valuable metals Fe, Mn, V, and Cr in V-slag at 800 °C

Table 2 The chlorination ratio of valuable metals for microwave and conventional heating at 800 °C

Treatment Method	Holding time	V Chlorination Ratio (%)	Cr Chlorination Ratio (%)	Mn Chlorination Ratio (%)	Fe Chlorination Ratio (%)	Ti Chlorination Ratio (%)
Conventional heating	8 h	72	61	80	66	51
Microwave heating	30 min	82.67	75.82	92.96	91.66	63.14



The chlorination valuable metals behavior of the microwave heating chlorination V-slag exhibited a higher chlorination ratio compared with the conventional heating. The chlorination ratio of Fe, Mn, V, Cr, and Ti was 91.66%, 92.96%, 82.67%, 75.82%, and 63.14%, respectively. Microwave heating significantly shortened the holding time of chlorination V-slag. Microwave heating had the advantage of rapid heating [12]. In this work, the V-slag-(NaCl-KCl)-AlCl₃ mixture sample proved to be a good microwave absorber and rose to 800 °C in 12 min by microwave heating. However, conventional heating required 3.5 h to 800 °C by 4000 W. Microwave heating greatly reduced the energy consumption. According to the calculation of the Fe, Mn, V, Cr, and Al ion concentration in the product, the mass balance of AlCl₃ in molten salt at 800 °C for 30 min was shown in Table 3. The volatilization ratio of AlCl₃ in the microwave heating at 800 °C for 30 min was 3.92%, while conventional heating at 900 °C for 1h was 8.97%. More AlCl₃ was fixed in the molten salt. The volatilization ratios of samples in microwave heating and conventional heating at different temperature were shown in Figure 9. At 900 °C, the volatilization ratio of V-slag-(NaCl-KCl)-AlCl₃ mixture sample in conventional heating reached 15% for 8 h, while the volatilization ratio of V-slag-(NaCl-KCl)-AlCl₃ mixture sample in microwave heating was only 3.12% for 30 min. The volatilization ratio of conventional heating chlorination V-slag sample was significantly higher than that of microwave heating. Shortening the heating time could stabilize more of AlCl₃ in the molten salt, which should reduce the volatilization of the AlCl₃.

The mechanisms of high-efficiency chlorination V-slag by microwave heating may be explained as follows: (1) Enhanced reaction rate. Microwave heating rapidly fixes AlCl₃ in the molten salt, increasing the concentration of AlCl₃. The coupling of microwave alternating electric field and molten salt medium enhances the reaction rate; (2) Stirring effects of microwave heating. The microwave furnace operates at frequency of up to 2.45 GHz, and the electric field component of the microwaves causes dipoles to rotate with the alternating field (2450 million times per second) [27]. The diffusion of molten salt ions and metal ions of molten salt media has been strengthened in the microwave field. (3) In the microwave field, the heating ratio of Si was very slow, but the heating ratio of V and Fe was fast [28]. Due to the difference of thermal expansion coefficient in spinel and olivine [29, 30], different absorbing capacity minerals generate a stress in the lattice. The stress causes cracks in the V-slag particles and increases the reaction area. (4) Local high temperature effect. V and Fe in V-slag as a good microwave absorber can be selectively heated by microwave. In the microwave heating process, sparks

Table 3 AlCl₃ participates in the material balance of microwave heating chlorination V-slag

Temperature (°C)	Time (min)	Chlorinated valuable metals (%)	Present in molten salt (%)	Volatilize (%)
800	30	53.10	42.98	3.92

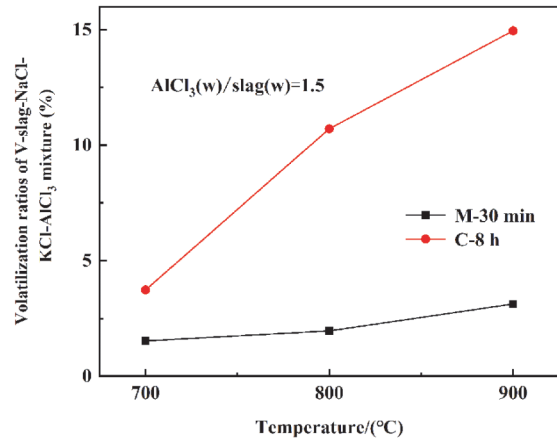


Figure 9. Volatilization ratio of microwave heating for 30 min and conventional heating for 8h chlorination V-slag-(NaCl-KCl)-AlCl₃ mixture at different temperature

or electric arcs phenomenon was observed. These sparks or electric arcs can be regarded as microplasmas at the microscopic level [27]. This may cause local high temperatures to promote the chlorination of valuable metals [31].

5. Conclusion

Microwave heating was an efficient method, which can chlorinate simultaneously valuable metals (V, Cr, Mn, Fe, and Ti) from V-slag. The following conclusions can be drawn from this study:

From the thermodynamic equilibrium, AlCl₃ can chlorinate valuable metals Fe, Mn, V, Cr, and Ti in V-slag. V-slag, V-slag-AlCl₃, and V-slag-(NaCl-KCl)-AlCl₃ mixture samples were good microwave absorbers with average heating rate of 134 °C/min, 120 °C/min, and 67 °C/min. In addition, the temperature could be stabilized by molten salt during microwave heating.

V-slag was treated by microwave heating under an optimal condition at 800 °C for 30 min. The chlorination ratios of valuable metals V, Cr, Mn, Fe, and Ti were 82.67%, 75.82%, 92.96%, 91.66%, and 63.14%, respectively. The volatilization ratios of AlCl₃ and V-slag-(NaCl-KCl)-AlCl₃ mixture sample were 3.92% and 1.96%, respectively. Microwave heating method reduced the volatilization ratio of AlCl₃, and its energy consumption was significantly lower than conventional heating method.



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References

- [1] R. Moskalyk, A. Alfantazi, Miner. Eng., 16(9) (2003) 793-805.
- [2] S.Q. Liu, Iron Steel Vanadium Titanium, 35 (2014) 55 (in Chinese).
- [3] X.S. Li, B. Xie, Int. J. Min. Met. Mater., 19(7) (2012) 595-601.
- [4] H.X. Fang, H.Y. Li, B. Xie, ISIJ Int., 52(11) (2012) 1958-1965.
- [5] J. Wen, T. Jiang, M. Zhou, H. Y. Gao, Int. J. Min. Met. Mater., 25(5) (2018) 515-526.
- [6] Y. L. Liao, G. C. Shi, F. R. Huang, J. Min. Metall. Sect. B-Metall., 55(3) (2019) 359-370.
- [7] S. Y. Liu, S. J. Li, S. Wu, L. J. Wang, K. C. Chou. J. Hazard. Mater., 354 (2018) 99-106.
- [8] P. M. Danilov, I. E. Podynogin, I. A. Vainshtein, Metallurgist, 18(2) (1974) 108-110.
- [9] S.Y. Liu, L.J. Wang, K.C. Chou, Ind. Eng. Chem. Res., 55(50) (2016) 12962-12969.
- [10] A. Abbasalizadeh, S. Seetharaman, L. Teng, JOM., 65(11) (2013) 1552-1558.
- [11] H. A. Hjuler, R. W. Berg, K. Zachariassen, N. J. Bjerrum, J. Chem. Eng. Data., 30(2) (1985) 203-208.
- [12] D. A. Jones, T. Lelyveld, S. Mavrofidis, Resour. Conserv. Recy., 34(2) (2002) 75-90.
- [13] R. Amankwah, G. Ofori-Sarpong, Miner. Eng., 24(6) (2011) 541-544.
- [14] A. de la Hoz, A. Diaz-Ortiz, A. Moreno, Chem. Soc. Rev., 34(2) (2005) 164-178.
- [15] M. Al-Harashsheh, S. Kingman, Hydrometallurgy, 73(3-4) (2004) 189-203.
- [16] H. Hao, H. Liu, Y. Liu, Mater. Res. Inovations, 11(4) (2007) 185-187.
- [17] Z. Huang, X. Deng, J. Liu, J. Ceram. Soc. Jpn., 124(5) (2016) 593-596.
- [18] Z. Peng, J. Y. Hwang, Int. Mater. Rev., 60(1) (2015) 30-63.
- [19] B. Sahoo, S. De, B. Meikap, Fuel Process. Technol., 92(10) (2011) 1920-1928.
- [20] P. Kumar, B. Sahoo, S. De, J. Ind. Eng. Chem., 16(5) (2010) 805-812.
- [21] J. W. Walkiewicz, A. E. Clark, S. L. McGill, IEEE Trans. Ind. Appl., 27(2) (1991) 239-243.
- [22] G.Q. Zhang, T.A. Zhang, G. Lü, JOM., 68(2) (2016) 577-584.
- [23] K. E. Haque, Int. J. Miner. Process., 57(1) (1999) 1-24.
- [24] Y. Ishitsuka, T. Ishikawa, R. Koborinai, Phys. Rev. B., 90(22) (2014) 224411.
- [25] D. E. Clark, W. H. Sutton, Annu. Rev. Mater. Sci., 26(1) (1996) 299-331.
- [26] R. G. Reddy, J. Phase. Equilib. Diffus., 32(4) (2011) 269-270.
- [27] J. Menéndez, A. Arenillas, B. Fidalgo, Fuel Process. Technol., 91(1) (2010) 1-8.
- [28] G.Q. Ou Yang, X.Y. Zhang, X.D. Tian, Chin. J. Nonferrous Met., 18(4) (2008) 750.
- [29] R. M. Hazen, Phys. Chem. Miner., 14(1) (1987) 13-20.
- [30] X.L. Shi, Y.H. Wang, K.H. Zhao, J. Cryst. Growth, 419 (2015) 102-107.
- [31] C. Liu, J.H. Peng, J. Liu, J. Hazard. Mater., 358 (2018) 198-20

EFIKASAN POSTUPAK EKSTARKCIJE V, Cr, Ti, Fe I Mn IZ VANADIJUMSKE ŠLJAKE MIKROTALASNIM ZAGREVANJEM

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Apstrakt

Vanadijumska šljaka (V-šljaka) nastaje topljenjem vanadijuma iz titanomagnetitne rude koja sadrži važne metale poput V, Ti, Cr, Fe i Mn. Tradicionalne metode su uglavnom fokusirane na ekstrakciju V i Cr postupkom oksidacije ili redukcije. U ovom radu je prikazana metoda hlorizacije koja zadržava valentno stanje svakog elementa u izvornom stanju. U radu je ispitivano mikrotalasno zagrevanje kao način za ubrzanje difuzije elemenata i smanjenja isparljivosti rastopljenih soli. Rezultati su pokazali da je bilo potrebno 30 minuta da se izvrši hlorizacija V-šljake na 800 °C, a odnos V, Cr, Mn, Fe i Ti prilikom hlorizacije je dostigao 82,67%, 75,82%, 92,96%, 91,66% i 63,14 %. U poređenju sa rezultatima koji su dobijeni prilikom standardnog zagrevanja tokom 8 h, brzina ekstrakcije mikrotalasnim zagrevanjem je pokazala veće prednosti. Pored toga, mikrotalasno zagrevanje je smanjilo isparljivost AlCl₃ skraćivanjem vremena reakcije. Odnos isparavanja AlCl₃ prilikom mikrotalasnog zagrevanja i standardnog zagrevanja je iznosio 3,92%, odnosno 8,97% (1 h). Mehanizam efikasne hlorizacije se može predstaviti kao unapređenje postupka difuzije jona i pojačana hemijska reakcija usled visoke temperature.

Ključne reči: Vanadijumska šljaka; Mikrotalasno zagrevanje; Rastopljena so; Efikasna hlorizacija

