Study on leaching Ti from Ti bearing blast furnace slag by sulphuric acid

T. Jiang, H. G. Dong*, Y. F. Guo, G. H. Li and Y. B. Yang

The treatment for leaching Ti using sulphuric acid was investigated in order to utilise Ti bearing blast furnace slag including water quenched slag (WQS) and naturally cooled slag (NCS). Ti bearing blast furnace slag was subjected to direct agitation leaching with dilute sulphuric acid. Variables such as acid concentration, temperature, leaching time, liquid/solid ratio, particle size and stirring speed were studied. It was shown that, when WQS material (size range, 0–0·5 mm) was reacted with sulphuric acid of 50% concentration at a stirring speed of 400 rev min^{-1} with a liquid to solid weight ratio of 10 at 100°C for 1 h, Ti recovery from leaching was up to 72·3%. However, for NCS, Ti recovery was only ~45% under comparative leaching conditions. A possible leaching mechanism and the difference of leaching effect between WQS and NCS are discussed. Unlike NCS, WQS is a type of activated slag, making it more favourable for extraction of Ti.

Keywords: Ti bearing blast furnace slag, Sulphuric acid leaching, Water quenched, Activation

Introduction

V–Ti bearing magnetite is composite ore containing Fe, V and Ti, in addition to many other valuable metals (such as Co, Ni, Cr, Sc, Ga, etc.). V–Ti bearing magnetite ores are abundant in Pan-Xi area of China. Reserves of Ti in the area account for 90·5% of total Ti resource.[1] Using the present process in Panzhihua Iron & Steel Company, a large amount of blast furnace slag containing 22–25%TiO_2 has been produced. Based on the method of cooling, the Ti bearing blast furnace slag (TBFS) was classified into water quenched slag (WQS) and naturally cooled slag (NCS). In considering the potential for producing synthetic rutile, titanium tetrachloride ($TiCl_4$) and titanium white, TiO_2 grade of TBFS was too low. For producing cement and concrete active blend, the TiO_2 grade of TBFS is too high, leading to poor hydraulicity of the raw material. As a result, TBFS material has been piling up largely as waste material.[2,3]

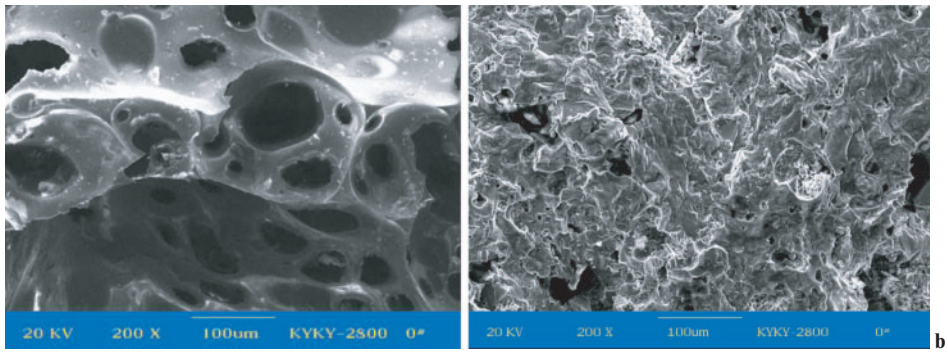
Several studies[4] on comprehensive utilisation of TBFS have been carried out in China from the 1960s. Owing to a greater specific surface area and strong absorbability, WQS has been used to treat with coal gas purified water.[5] However, the method is still not industrialised because of limited production capacity, and the valuable Ti resource is not recovered. The Institute of Pan Steel has developed two new technologies to produce $TiCl_4$ with TBFS. Using silicothermic process, Si–Ti alloy was obtained as the reduction reagent for ferrosilicon containing 75%Si. TiO_2 in the TBFS was reduced and carbonised in an electric furnace; then, the TiC was chlorinated under low temperature to obtain $TiCl_4$. To some extent, Ti resource was utilised synthetically by these methods. However, the technologies have some disadvantages, especially as the electricity consumption and costs are very high so that these processes are not industrialised on a large scale.[6] On the basis of physical and chemical characteristics of TBFS, the technology for Ti component enrichment separation has been investigated to enrich Ti as a mineral phase with a definite reclaimable particle size; Ti bearing phase was separated from the slag. Ti component in TBFS was enriched selectively as $CaTiO_3$ phase with an average grain size of 55 μm using a roasting temperature of 1723 K for 20 min followed by cooling at 0·5 K min^{-1}. The Ti rich material with the grade 38·9% has been obtained by flotation.[7] Investigation showed that Ti component in TBFS was enriched selectively as rutile (TiO_2) phase by pre-oxidisation, incorporation of additives and a high temperature treatment.[8] The investigation[9] indicated that the addition of SiO_2 and slow cooling rate were favourable in improving crystallisation of anosvite ($Ti_2O_3.TiO_2$) under a reducing atmosphere. Crystallisation of anosvite ($Ti_2O_3.TiO_2$) was up to 19% with a SiO_2 dosage of 25%. However, the conditions used in those treatments above were harsh. Separation was low due to the fine particle size of Ti bearing phases. The experiments were carried out in the lab and have not been adopted on an industrial scale.

Hydrometallurgical extraction of Ti is advantageous from the point of view of dust generation, ease of technology and reaction conditions and also easy implementation in industrial production. The investigation[10] showed that TiO_2 extraction of 88% could be obtained from TBFS using concentrated sulphuric acid (89–93 mass-%). After removing iron by magnetic separation, TBFS was leached out under pressure with dilute sulphuric acid[11,12] (20–60 mass-%), and Ti recovery by

School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China

*Corresponding author, email donghaigang0404@126.com

Published by Maney on behalf of the Institute and The AusIMM
Received 5 December 2007; accepted 16 November 2009
DOI 10.1179/037195509X12585446038807



a b

a WQS; *b* NCS

1 Image (SEM) of TBFS ×200

leaching was >85%. However, additional consumption of sulphuric acid on dissolving CaO, MgO and Al_2O_3 in the matrix could result in a higher cost and increased environmental contamination. Pressure leaching as an alternative option needs air tight and pressure equipment, which will lead to high cost and increased complexity in the process.

Therefore, it is very necessary to explore a reasonably simple and a more economic process to recover Ti by hydrometallurgical extraction method from TBFS. In the present paper, the feasibility of recovering Ti by dilute sulphuric acid (10–60%) from TBFS (including WQS and NCS) of Pan Steel was investigated under normal atmosphere. In addition, the mechanism of leaching and the difference of leaching behaviour between WQS and NCS are described.

Experimental

Materials

The materials used in the present study were offered by Panzhihua Iron & Steel Company and their compositions are given in Table 1.

Table 1 indicated that the compositions of WQS and NCS were comparative, although they were cooled at different rates.

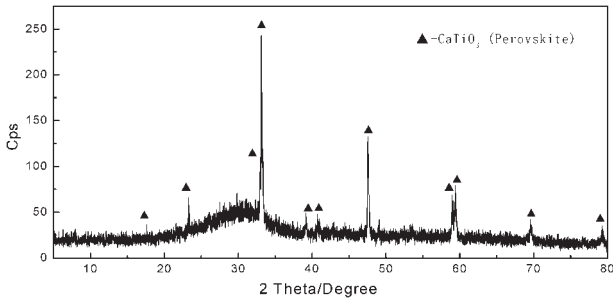
Macroscopic appearance and microscopic morphology of the TBFS sample were recorded by SEM (Fig. 1).

Main minerals in NCS

According to the literature,[13] the main Ti bearing minerals in NCS are perovskite and titanaugite, and the TiO_2 content in the perovskite accounts for ~55% of the total TiO_2. Secondary mineral is spinel, which aggregates strongly with perovskite. Distribution of Ti is dispersive; each mineral in NCS contains Ti.

Main minerals in WQS

The main minerals in WQS were analysed by X-ray diffraction (XRD). The results are shown in Fig. 2. Results of XRD results show that there is only one crystal phase of perovskite ($CaTiO_3$) in the sample, but a large diffused diffraction peak centred at ~30° 2θ indicates that non-crystalline substances are present in the sample. Therefore, according to XRD results, Ti occurred as $CaTiO_3$ mainly in the slag, but there should be a fraction of Ti existing as non-crystalline substances.



2 X-ray diffraction pattern of WQS

Leaching experiments

At selected ratios of liquid/solid (L/S), the sample of TBFS (with a granularity) and sulphuric acid at a selected concentration were well mixed at a constant temperature reactor with an agitator. After the reaction was allowed to occur for a certain time, the reaction mixture was filtered. After being dried and weighed, the productivity of the filter residue was calculated (the mass percentage of filter residue over raw material), and the chemical composition of the filter residue was analysed. The leaching effect of the TBFS was judged by the Ti leaching, which was calculated by the following equation

$$\eta = (1 - \frac{\beta\gamma}{100\alpha}) \times 100 \quad (1)$$

where η is Ti leaching, α the Ti grade of raw material, β the Ti grade of the filter residue and γ productivity of the filter residue (all in %).

Analytical reagent grade sulphuric acid and distilled water were used in all experiments.

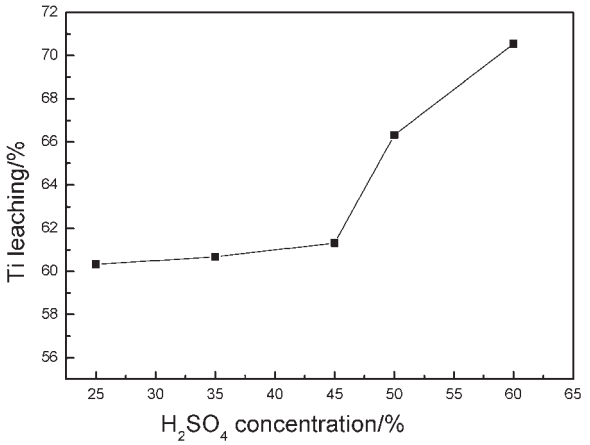
Analysis techniques

The chemical compositions of all residues were detected by BFT minifluorescence analysis instrument.

An XRD (Philips, The Netherlands) was used to determine the mineral phases present. The voltage and anode current used were 40 kV and 40 mA respectively.

Table 1 Chemical composition of materials

Slag species	Fe_{total}	TiO_2	CaO	SiO_2	MgO	Al_2O_3	Na_2O	K_2O	MnO
WQS, %	1·16	22·36	27·81	23·46	7·98	13·89	0·35	0·73	0·73
NCS, %	1·80	22·00	26·28	22·80	7·14	12·30	0·40	0·83	0·74



3 Effect of sulphuric acid concentration on Ti leaching for WQS

The wavelength was from Cu K_α=0·15405 nm, and the diffraction was performed in a continuously scanning mode with 0·02 interval and 0·25 s set time used to collect the XRD patterns of samples.

Micromorphology of the slag was observed using a JEOL/EO JSM-5900 SEM at an accelerating voltage of 20 kV.

Results

Leaching tests of WQS

Effect of sulphuric acid concentration on Ti leaching

Under the conditions of leaching time of 2 h, leaching temperature of 80°C, L/S ratio of 10, material particle size of 0–3·5 mm and stirring speed of 400 rev min^{-1}, the effect of sulphuric acid concentration (mass fraction) on Ti leaching is shown in Fig. 3.

It can be seen from Fig. 3 that the Ti leaching increased with increasing the concentration of sulphuric acid. Ti leaching increased sharply when sulphuric acid concentration was >45%, which possibly resulted from the dissolution of Ti from the other minerals phases present. During the experimental process, a white colloid substance was found when sulphuric acid concentration was >45%. Chemical composition of the white colloidal substance was analysed, and results are given in Table 2 and the XRD of the substance shown in Fig. 4.

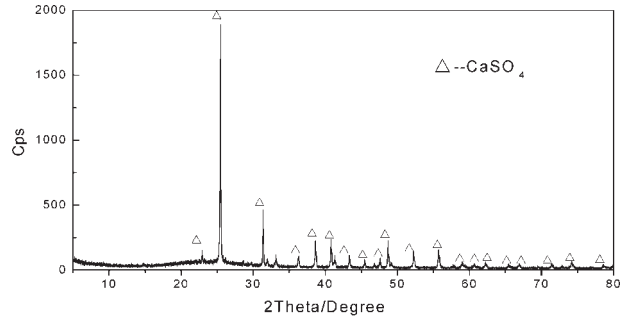
From Table 2 and Fig. 4, it can be concluded that the white colloidal substance was $CaSO_4$. The conclusion was in accordance with the literature investigation,[14] which would affect possibly the Ti leaching.

Effect of leaching time on Ti leaching

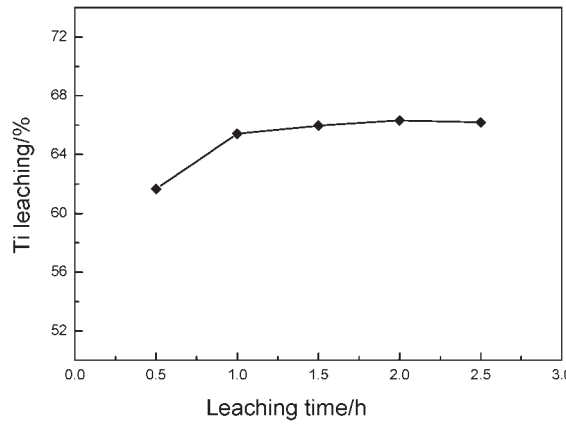
The reaction between the 0–3·5 mm material and sulphuric acid at 50% concentration with an L/S ratio of 10 and a stirring speed of 400 rev min^{-1} was studied at 80°C while varying the leaching time from 0·5 to 2·5 h. The results in Fig. 5 showed that Ti leaching increased with leaching time, but when leaching time was more than 1 h, Ti leaching did not increase any further. Meanwhile, it was observed that the quantity of white colloid substance increased gradually with leaching time. Ti leaching did not exceed 67% due to the formation of this white colloidal substance.

Table 2 Chemical composition of white colloid substance

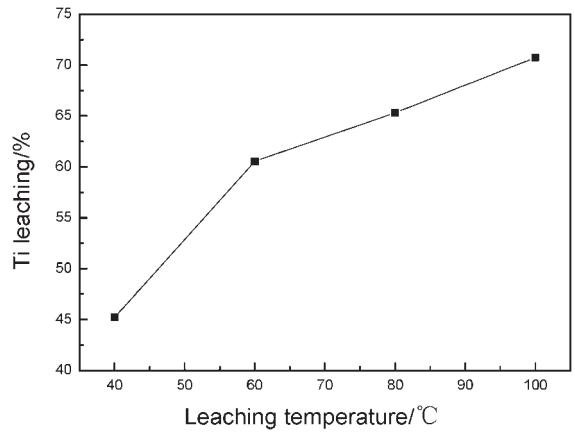
Elements	O	S	Ca	Ti	Al	Si	Fe
Percentage, %	56·40	17·50	23·79	1·77	0·06	0·33	0·04



4 X-ray diffraction pattern of white colloid substance



5 Effect of leaching time on Ti leaching for WQS



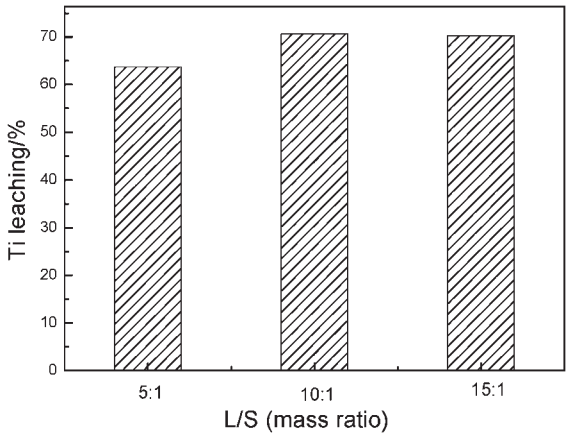
6 Effect of leaching temperature on Ti leaching for WQS

Effect of leaching temperature on Ti leaching

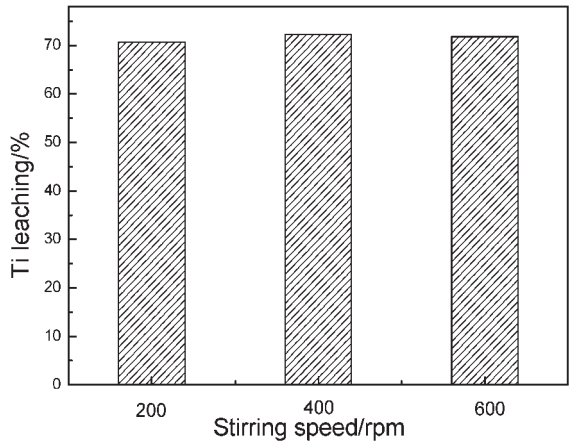
Figure 6 showed that the increase in temperature was found to be effective in increasing Ti leaching under the conditions of 50% sulphuric acid concentration, 0–3·5 mm material at L/S ratio of 10 with a stirring speed of 400 rev min^{-1} for 1 h. Ti leaching was ~71% when leaching temperature was 100°C. This might be in favour of diffusion of sulphuric acid on the surface of the slag and improves the reaction rate.

Effect of particle size on Ti leaching

A set of experiments were carried out to examine the effect of particle size under reaction conditions of 50% sulphuric acid concentration, leaching time of 1 h, L/S



7 Effect of L/S ratio on Ti leaching for WQS



8 Effect of stirring speed on Ti leaching for WQS

ratio of 10, leaching temperature of 100°C and stirring speed of 400 rev min^{-1}. The results are shown in Table 3.

It is shown in Table 3 that the finer the particle size is, the greater Ti leaching becomes. The leaching of Ti was 72·3% when particle size was <0·5 mm, while Ti leaching was only 73·6% when particle size was <0·074 mm. However, the particle size of the material was too fine, reaction rate was quick and the material would cling to the surface of the reactor. The best leaching of Ti would be obtained when particle size of material was <0·5 mm.

Effect of L/S ratio on Ti leaching

These experiments were performed to find the suitable L/S ratio for Ti leaching. All the other leaching conditions were kept constant as given before while varying the L/S ratio from 5 to 15. The results are shown in Fig. 7.

It was found that the liquid will not fully cover the solid if the L/S ratio was <5 due to the loose and porous structure of the slag. From Fig. 6, L/S ratio did not affect Ti leaching when the L/S ratio was >10.

Effect of stirring speed on Ti leaching

Several experiments were carried out to explore the effect of stirring speed on Ti leaching under reaction conditions of 50% sulphuric acid concentration, leaching time of 1 h, material granularity of 0–0·5 mm, leaching temperature of 100°C and L/S ratio of 10. The results are shown in Fig. 8.

From Fig. 8, it was found that Ti leaching changed a little when stirring speed increased. It could be concluded that the leaching reaction was not controlled by diffusion but by chemical reaction.

Therefore, for WQS, other minerals bearing silica and calcium were leached by sulphuric acid during the leaching process, and the white colloidal substance, namely $CaSO_4$, was produced, which made the ore pulp viscous and covered over the surface of the material and hindered the diffusion of sulphuric acid. Therefore, the Ti leaching could not be increased any further, and the Ti leaching recovery was ~72%. However, in other hydrometallurgical treatments, the Ti leaching was reported to be >85% using concentrated sulphuric acid (98 mass-%) and with pressure leaching.[10,11] Therefore, the key reason for low Ti leaching in the present work was the formation of $CaSO_4$. If this problem could be solved, Ti leaching could be increased. Investigations should be carried out to avoid the formation of $CaSO_4$ or weaken its influence on the leaching to improve the Ti leaching from the slag.

Table 3 Effect of particle size on Ti leaching for WQS

Particle size, mm	0–0·074	0–0·5	0–1·0	0–3·5
Ti leaching, %	73·6	72·3	71·0	70·7

Leaching tests of NCS

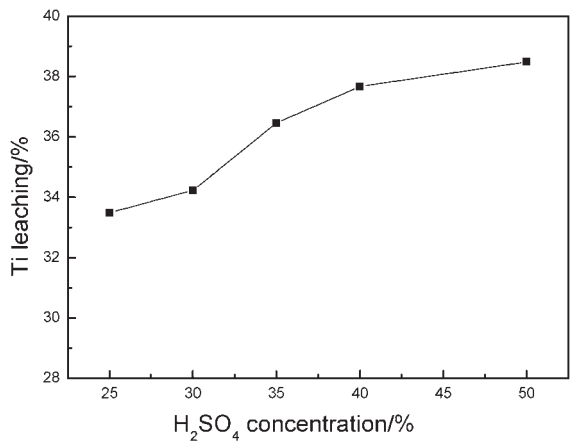
Effect of sulphuric acid concentration on Ti leaching

A set of experiments were performed at 100°C. The leaching process was carried out by mixing 0–0·105 mm material with sulphuric acid under a stirring speed 400 rev min^{-1} with an L/S ratio of 10 for 1 h. The results are shown in Fig. 9.

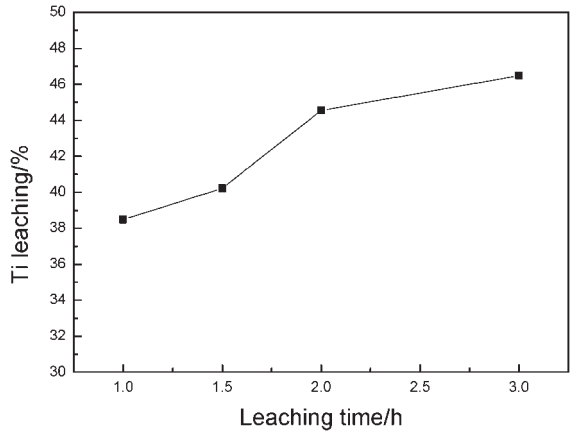
Figure 9 illustrated that Ti leaching in NCS did not exceed 40%, which was less than in WQS. The white colloidal substance, as mentioned before, was not observed in the leaching process of NCS. The Ti leaching was low, possibly resulting from the characteristics of NCS.

Effect of leaching time on Ti leaching

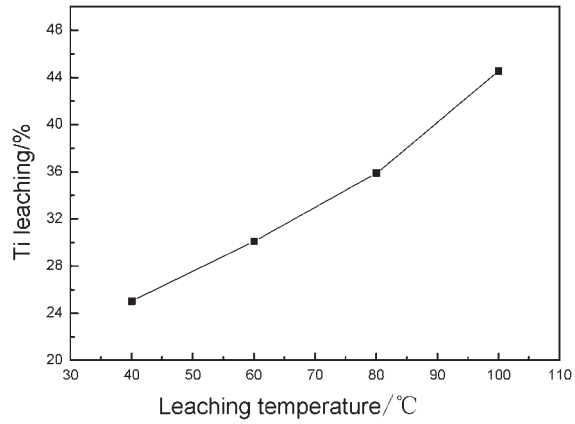
The effect of leaching time on Ti leaching was carried out under leaching conditions of 50% sulphuric acid concentration, material granularity of 0–0·105 mm, leaching temperature of 100°C, stirring speed of



9 Effect of sulphuric acid concentration on Ti leaching for NCS



10 Effect of leaching time on Ti leaching for NCS



11 Effect of leaching temperature on Ti leaching for NCS

400 rev min^{-1} and L/S ratio of 10. The results are shown in Fig. 9.

It is illustrated in Fig. 10 that with the extending of leaching time, Ti leaching increased. Ti leaching increased rapidly within the first 2 h and then remained steady.

Effect of leaching temperature on Ti leaching

A set of experiments were carried out to examine the effect of temperature on Ti leaching. These experiments were conducted using 50% sulphuric acid concentration and 0–0·105 mm material size at an L/S ratio of 10 for 2 h under a stirring speed of 400 rev min^{-1}. The results are illustrated in Fig. 11.

Figure 11 revealed that increasing the leaching temperature is favourable for Ti leaching. Nevertheless, Ti leaching with sulphuric acid at various temperatures was <45%. Even if the leaching temperature is 100°C, Ti leaching was ~45%. This might be attributed to the presence of refractory minerals in NCS.

Effect of particle size on Ti leaching

The reactions between the material of different granularities and 50% sulphuric acid agitated at 400 rev min^{-1} speed with an L/S ratio of 10 at 100°C for 2 h. The results are illustrated in Table 4.

The results in Table 4 showed that the Ti leaching increased with the decrease in particle size. However, it was found that when the particle size of material was too fine while the reaction rate was fast, the products were consolidated in the reactor due to the rapid release of heat.

For NCS, the maximum Ti leaching was ~45%. The characteristic of NCS has determined the Ti leaching. Therefore, to increase Ti leaching, other measures should be used to change the characteristic of NCS. The main reason of NCS's lower leaching is its higher crystallinity compared to the WQS.

Studies on mechanism of leaching process

Thermodynamics

Reactions involved in acid leaching of TBFS are very complex. It was necessary to find out the feasibility and the maximum extent of reactions. Thermodynamic data of the relevant reactions are given below.

Table 4 Effect of particle size on Ti leaching for NCS

Particle size, mm	0–3·5	0–0·5	0–0·105
Ti leaching, %	23·3	31·3	44·6

$\Delta G^{o}_{f,298}(TiO^{2+})$ and $\Delta G^{o}_{f,298}(Ti^{3+})$ could be obtained by the following equations[15–18]

$$TiO^{2+} + 2H^{+} + 4e \rightarrow Ti + H_2O,\ \phi^{o} = -0{\cdot}89V \quad (2)$$

$$\Delta_r G^{o}_{298} = -n\phi^{o}F = 343{\cdot}54\,kJ\,mol^{-1} \quad (3)$$

$$TiO^{2+} + 2H^{+} + e \rightarrow Ti^{3+} + H_2O,\ \phi^{o} = 0{\cdot}1V \quad (4)$$

$$\Delta_r G^{o}_{298} = -n\phi^{o}F = -9{\cdot}65\,kJ\,mol^{-1} \quad (5)$$

From equations (2)–(5), the following values were obtained

$$\Delta G^{o}_{f,298}(TiO^{2+}) = -589{\cdot}73\,kJ\,mol^{-1}$$

$$\Delta G^{o}_{f,298}(Ti^{3+}) = -353{\cdot}19\,kJ\,mol^{-1}$$

Based on thermodynamic data,[18] $\Delta_r G^{o}_{298}$ of possible reactions between sulphuric acid and TBFS are given in Table 5.

As shown in Table 5, among these reactions of titaniferous minerals with sulphuric acid, only the $\Delta_r G^{o}_{298}$ value of reaction between $CaTiO_3$ and sulphuric acid is negative. It can be concluded that Ti bearing minerals in the slag are not insoluble in H_2SO_4 but in $CaTiO_3$.

The XRD of WQS showed that the main minerals in WQS are perovskite ($CaTiO_3$) and non-crystalline substances. The main Ti bearing minerals[13] in NCS are perovskite (accounts for 55% of the total TiO_2) and insoluble titanaugite in H_2SO_4. Therefore, the Ti leaching for WQS is higher than that for NCS after leaching using H_2SO_4.

Effect of crystallisation

Because non-crystalline substance is of short range order and in metastable state, the energy is not at the lowest state, while the crystalline mineral is at the lowest energy state. Therefore, breaking up the structure of a crystalline mineral needs greater external energy than breaking a non-crystalline mineral.[19,20]

Water quenched slag was rapidly cooled by high pressure water in refining processing of blast furnace. Formation and growth of crystalline core were limited. Therefore, lots of non-crystalline substances were formed besides $CaTiO_3$ with crystal defect in this slag.

Table 5 $\Delta_r G^{\circ}_{298}$ of possible reactions between sulphuric acid and TBFS

Equations	$\Delta_r G^{\circ}_{298}$, kJ mol^{-1}
$CaTiO_3+4H^++SO_4^{2-}\rightarrow CaSO_4+TiO^{2+}+2H_2O$	−91·12
$Ti_3O_5+8H^+\rightarrow TiO^{2+}+Ti^{3+}+4H_2O$	261·84
$CaO{\cdot}TiO_2{\cdot}SiO_2+4H^++SO_4^{2-}\rightarrow TiO^{2+}+CaSO_4+2H_2O$	5·51
$CaO{\cdot}MgO{\cdot}2SiO_2+4H^++SO_4^{2-}\rightarrow CaSO_4+Mg^{2+}+2SiO_2+2H_2O$	−122·13
$2CaO{\cdot}Al_2{\cdot}O_3{\cdot}SiO_2+10H^++2SO_4^{2-}\rightarrow 2CaSO_4+2Al^{3+}+SiO_2+5H_2O$	971·61
$TiO_2+2H^+\rightarrow TiO^{2+}+H_2O$	141·82
$CaO+2H^++SO_4^{2-}\rightarrow CaSO_4+H_2O$	−314·51
$MgO+2H^+\rightarrow Mg^{2+}+H_2O$	−87·76
$Al_2O_3+6H^+\rightarrow 2Al^{3+}+3H_2O$	−91·58

Therefore, it could be conclude that water quenching played a role in activating the slag in the cooling process. This activated slag was more favourable for extracting Ti by hydrometallurgy process, while NCS was naturally cooled in air and various Ti bearing minerals and aluminosilicates with good crystallinity were formed. In hydrometallurgical leaching, more energy is needed to destroy the crystalline structure. For these reasons, under comparative leaching conditions, Ti leaching effect of TiO_2 for WQS was better than that for NCS by sulphuric acid.

Effect of morphology of slag

From Figs. 1 and 2, it can be concluded that the body of WQS is loose, and the strength of the particle itself is low. Sulphuric acid easily penetrates through the inner micropore of the slag, which improved the reaction rate and strengthened the leaching process, and the Ti leaching is >72% within 1 h under optimum conditions, while compact structure of NCS hindered the diffusion of sulphuric acid, which decreased the reaction rate. Hence, the difference of the two types of slag in terms of morphology is another reason for the different Ti leaching behaviours.

Conclusions

The present paper involved the feasibility and behaviours of Ti leaching by dilute sulphuric acid from TBFS. Two kinds of slag, WQS and NCS, were investigated, and the following conclusions are made.

1. For WQS, a Ti leaching up to 72% was obtained by stirring leaching with sulphuric acid at a concentration of 50%, L/S ratio of 10 and a stirring speed of 400 rev min^{-1} at the temperature of 100°C for 1 h. However, for NCS, only ~45% Ti leaching was obtained under comparative leaching conditions of WQS.
2. Thermodynamic analysis showed that the titaniferous mineral dissolving in the sulphuric acid is perovskite; the presence of non-crystalline substances and defect crystallinity of $CaTiO_3$ as well as loose structure for WQS resulted in a greater Ti leaching than for NCS.
3. For WQS, the formation of $CaSO_4$ (white colloidal substance) occurred during the leaching process, which affected further increase in Ti leaching.

Acknowledgement

The authors thank the National Natural Science Foundation of China Program (grant no. 50504018) for the financial support of the present research.

References

1. H. G. Du: 'Theory for blast furnace refining V and Ti-bearing magnetite'; 1996, Beijing, Science Press.
2. C. L. Duan, A. K. Mi, Q. Y. Zhang and X. C. Guo: 'Utilization of titaniferous resources in Panxi', *Multipurp. Utiliz. Min. Resour.*, 2000, (2), 30–34.
3. Y. H. Li, T. P. Lou and Y. H. Xia: 'Kinetic of non-isothermal precipitation process of the perovskite phase in $CaO–TiO_2–SiO_2–Al_2O_3–MgO$ system', *J. Mater. Sci.*, 2000, **35**, (22), 5635–5637.
4. C. X. Li, H. Wang, R. X. Li and X. Y. Yang: 'Development of study on comprehensive utilization of titanium-bearing blast furnace slag', *J. Shenyang Univ. Technol.*, 2004, **26**, (5), 495–498.
5. J. Z. Zheng and L. J. Tang: 'Application of water granulated slag to dispose of blast furnace gas cleaner effluents', *Ind. Water Treat.*, 2001, **21**, (2), 43–44
6. T. P. Lou: 'Selective precipitation and growth of Ti-rich phase in titanium-bearing blast furnace slags', PhD thesis, Northeastern University, Shenyang, China, 1999.
7. Z. T. Sui and P. X. Zhang: 'Precipitation selectivity of boron compounds from slags', *Acta Mater.*, 1999, **47**, (4), 1337–1344.
8. Y. H. Li: 'Selective precipitation and growth of perovskite phase in titanium-bearing blast furnace slag', PhD thesis, Northeastern University, Shenyang, China, 2000.
9. Y. W. Mao, W. B. Fang and H. W. Zhang: 'Modified treatment of Ti-bearing blast furnace slag of Pan Steel: crystal rule of perovskite', Proc. Natl Conf. on 'Metallurgical physical chemistry', Guangzhou, China, November 1994, The Chinese Society for Metals, 493–497.
10. Q. F. Chen: 'Extended test of extracting TiO_2 and Sc_2O_3 from Pan Steel Ti-bearing blast furnace slag', *Iron Steel Vanad. Titan.*, 1995, **16**, (3), 64–68.
11. X. H. Liu and Z. T. Sui: 'Pressure leaching of Ti-bearing blast furnace slag', *Trans. Nonferr. Met. Chn*, 2002, **12**, (6), 1281–1284.
12. M. H. Wang, X. H. Du and Z. T. Sui: 'Recovery of titanium from rich titanium blast-furnace slag by sulfate method', *Multipurp. Utiliz. Miner. Resour.*, 2000, (4), 5–8.
13. Y. T. Li: 'Application mineralogy', 296; 1995, Beijing, Science Press.
14. F. Yan, C. Li and B. Liang: 'A study on acidulation behavior of the silicon containing material in water quenched Ti-bearing furnace slag', *Multipurp. Utiliz. Miner. Resour.*, 2007, (6), 22–26.
15. Z. Q. Gong: 'Introduction of theoretical electro-chemistry', 1988, Changsha, Central South University of Technology Press.
16. Q. H. Zeng: 'Physical chemistry', 1996, Changsha, Central South University of Technology Press.
17. K. C. Sole: 'Recovery of titanium from the leach liquors of titaniferous magnetites by solvent extraction. Part I. Review of the literature and aqueous thermodynamics', *Hydrometallurgy*, 1999, **51**, 239–253.
18. D. L. Ye and J. H. Hu: 'Handbook of thermodynamic data on practical inorganic matter', 2002, Beijing, Metallurgical Industry Press.
19. B. C. Yang and X. G. Zhong: 'Solid physics', 2002, Changsha, Central South University of Technology Press.
20. S. T. Huang: 'Structure and structural analysis of non-crystal material', 1987, Beijing, Science Press.