Effects of Preheating Temperature and Time of Hongge Vanadium Titanomagnetite Pellet on Its Gas-Based Direct Reduction Behavior with Simulated Shaft Furnace Gases

Wei LI, Nan WANG, Guiqin FU, Mansheng CHU and Miaoyong ZHU*

School of Metallurgy, Northeastern University, Shenyang Liaoning, 110819 China.

(Received on August 16, 2017; accepted on December 26, 2017; J-STAGE Advance published date: February 14, 2018)

As a part of ongoing efforts to develop a novel clean smelting process of Hongge vanadium titanomagnetite (HVTM), the effects of preheating temperature and time of HVTM pellet (HVTMP) on its gas-based direct reduction behavior with simulated shaft furnace gases were investigated in this paper. The results showed that the compressive strengths of preheated and roasted HVTMP could be improved by increasing the preheating temperature and time to some extent. The induration mechanism of HVTMP with different preheating conditions was further deeply explained. Increasing the preheating temperature and time of HVTMP accelerated its subsequent reduction rate, however, from 900 to 1 000 °C, the reduction rate decreased. The preheating temperature and time of HVTMP had little effect on the final phase composition of reduced HVTMP. A schematic illustration was proposed to describe the effects of preheating temperature and time of HVTMP on its subsequent reduction swelling. In the practical industrial production of HVTMP, the preheating characteristics should be optimized to meet the requirements of compressive strength and reduction swelling of HVTMP smelting in the gas-based shaft furnace. This study aims to provide both theoretical and technical basis for the effective utilization of HVTM either in blast furnace or shaft furnace.

KEY WORDS: Hongge vanadium titanomagnetite pellet; preheating; compressive strength; reduction behavior; swelling.

1. Introduction

Vanadium titanomagnetite (VTM) is a kind of multi-element-coexistent mineral throughout the world.1–3) In Panx-Hongge district of China, there are more than 3.55 billion tons of VTM resources.4) The Hongge vanadium titanomagnetite (HVTM) is not only rich in valuable elements including iron, titanium, and vanadium, but also chromium. The reserve of chromium is 900 Mt, accounting for 68% of the chromium reserve in China.5) Therefore, it is of great importance to study the utilization of this special mineral resource.

At present, the blast furnace (BF) process is the main operating means for melting VTM to produce hot metal and slag with the content of TiO2 varying from 22% to 25%, but it is very hard to extract titanium components through traditional separation processes so far.6) Compared with the BF process, several new processes on the basis of direct reduction containing coal of HVTM or other minerals have been widely studied.7–17) Zhao et al.8) surveyed the reduction behaviors of FeO-V2O3 and FeO-Cr2O3 during coal-based direct reduction of HVTM and the effects on the elements distribution in the subsequent magnetic separation. Hu et al.11) examined the effect of Fe–Si on the carbothermic reduction of Panzhihua titanomagnetite concentrates under argon atmosphere. Paunova et al.13) studied the thermodynamics of reduction of titanomagnetite concentrate with solid carbon in different stoichiometric proportions between 973 and 1 273 K. Despite these studies conducted, the recovery rates of titanium, vanadium, and chromium are still quite low. In addition, it should be mentioned that the solid state carbothermic reduction is relatively low efficient with high-energy consumption and high operating temperature.18) So, HVTM has not been exploited and utilized on a large scale so far.

In order to improve the utilization efficiency of HVTM, a novel clean smelting process has been proposed by the authors’ laboratory, in which the recovery rates of valuable elements were evidently increased.19) In this process, HVTM were pelletized and oxidizing roasted initially, then reduced in a gas-based shaft furnace. Subsequently, the reduced pellets were melting separated for comprehensive recovery of iron, titanium, vanadium, and chromium. Obviously, gas-based shaft furnace direct reduction of oxidized pellets is a key procedure in this novel clean smelting process. No matter BF or gas-based shaft furnace is used, the use of oxidized pellets as a major part of the ferrous burden in this process presents many advantages, such as high physical strength, uniform size, and low degradation. Pelletizing
is one of the most widely used agglomeration techniques, which requires preparation of green pellets from fine concentrates and indurating them at high temperatures to get the required metallurgical properties. The metallurgical properties of oxidized pellets play a vital role in the productivity increase. In recent years, the oxidation roasting and gas-based direct reduction of titaniferous or other iron oxides have been widely investigated by a large amount of researchers.\textsuperscript{21–27} Zhang et al.\textsuperscript{21} studied the morphological changes and phase transition behaviors for the weak reduction of preoxidized Panzhihua ilmenite by hydrogen. Chen et al.\textsuperscript{24} investigated the effects of different parameters such as the size, preheating conditions, and roasting conditions on the roasting characteristics of vanadium titanomagnetite pellet. The oxidation roasting process of pellet will inevitably affect its subsequent gas-based direct reduction process. However, almost all the reports have been focused on ordinary ores,\textsuperscript{28–32} the reduction behavior about HVTM, especially the relation between oxidation roasting process of HVTM pellet (HVTMP) and its gas-based direct reduction process with simulated shaft furnace gases still remained unclear. Besides, the iron oxides used in the previous investigations were mainly high grade iron ore that can be used directly in iron making processes, the gas-based direct reduction of HVTMP with simulated gas compositions of HYL-III direct reduction process is presumably much more complicated than ordinary iron oxides due to its low content of iron, high content of titanium, chromium, and impurities, plus complex compositions. Under this backdrop, the results presented by previous studies may not be suitable for the gas-based direct reduction of HVTMP. Therefore, further investigation is imperative.

As a part of ongoing efforts to develop a novel clean smelting process of HVTM, in our previous study,\textsuperscript{33} the effect of roasting conditions of HVTMP on its subsequent reduction behavior with simulated shaft furnace gases has been accomplished. However, as we know, the production process of HVTMP undergoes two stages of high temperature treatment that are preheating stage and roasting stage, and many reactions occur in the preheating stage. Moreover, the effect of preheating conditions of HVTMP on the reduction process has not been understood adequately. Exploring the reduction behavior of HVTMP with different preheating conditions is necessary for the efficient utilization of HVTM. Thus, based on the study on the influence of roasting characteristics on gas-based direct reduction behavior of HVTMP, in the present research, the work is further proceeded, which mainly focuses on the effects of preheating temperature and time of HVTMP on its subsequent reduction behavior with simulated shaft furnace gases. The results obtained in the present work will be useful for determining appropriate preheating conditions in the production of HVTMP and provide both theoretical and technical basis for the industrial application.

2. Experimental

2.1. Materials

HVTM used in this study was obtained from Panxi-Honge district of China. The main chemical composition of HVTM is listed in Table 1 and it is characterized by a relatively high mass content of \( \text{Cr}_2\text{O}_3 \) compared with ordinary VTM. The phase composition of HVTM was investigated by X-ray diffraction (XRD). In order to analyze conveniently, only iron, titanium, vanadium, and chromium were marked in the XRD patterns. Figure 1 indicates that the phase compositions are complex and the main phases are magnetite (Fe\(_3\)O\(_4\)), titanomagnetite (Fe\(_{2.75}\)Ti\(_{0.25}\)O\(_4\)), coulsonite (Fe\(_2\)VO\(_4\)), and chromite (FeCr\(_2\)O\(_4\)).

2.2. Procedure

HVTM was mixed with 8.5% water and 1% bentonite and ballied into green pellets in an experimental balling disc pelletizer. The green pellets with a diameter of 11.5 to 12.5 mm were dried in an oven at 105°C for 5 h. Oxidation roasting experiments were carried out in a muffle furnace. When the muffle furnace was heated to the preheating temperature, the dried pellets were placed into the furnace and air was blown into the furnace to maintain an ample oxidizing atmosphere. After preheating, the temperature was increased to the roasting temperature of 1200°C and maintained 20 min. At last, the pellets were taken out of the furnace and air-cooled to ambient temperature.

Reduction experiments were conducted using a high-temperature electric resistance furnace. When the furnace was heated to the target temperature, the HVTMP were placed into the furnace with the protection of nitrogen atmosphere. After stabilization of the temperature, the atmosphere was changed to reducing gas mixture simulating the gas compositions of HYL-III shaft furnace to start the reduction process, the gas compositions were 64.3%\( \text{H}_2 \) + 25.7%\( \text{CO} \) + 5%\( \text{CO}_2 \) + 5%\( \text{N}_2 \) gas mixtures.\textsuperscript{39} The weight change during the reduction experiments was recorded by the computer at 30 s intervals. When the experiments were finished, the reduced pellets were taken out of the furnace quickly and cooled down under the protection of argon atmosphere.

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Chemical composition of HVTM (wt%).</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFe</td>
<td>FeO</td>
</tr>
<tr>
<td>54.54</td>
<td>26.25</td>
</tr>
</tbody>
</table>

Fig. 1. XRD patterns of HVTM.
In this study, the reduction degree \((R)\) is calculated through the formula:

\[
R = \left( \frac{0.11 w_1 + m_t - m_0}{m_0 w_2 \times 0.43} \right) \times 100\% \quad (1)
\]

where \(w_1\) is the ferrous content in the oxidation pellet, \%; \(m_t\) is the initial mass of pellet after removal of moisture, g; \(m_t\) is the mass of pellet after each reduction time \(t\), g; \(w_2\) is the content of total iron before reduction, \%; \(m_0\) is the initial mass of pellet, g; 0.11 is the necessary conversion factor of corresponding amount of oxygen making FeO oxidized to Fe\(_2\)O\(_3\); 0.43 is the conversion factor of corresponding amount of oxygen making all TFe oxidized to Fe\(_2\)O\(_3\).

The volume swelling index is defined as follows:

\[
\text{Swelling Index} = \frac{(V_a - V_0)}{V_0} \times 100\% \quad (2)
\]

where \(V_a\) is the volume of the pellets after reduction, \%, and \(V_0\) is the volume of the pellets before reduction, \%.

### 2.3. Characterization

The compressive strength and reduction swelling were detected by ISO4700 and ISO 4689:2007, respectively. Scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) analysis was used to examine the microstructures of the pellets. The measuring position in the pellets was at a depth of 3 mm from the outside to the inside of the cross section of the pellets. The phase compositions were identified by X-ray diffraction (XRD) analysis.

### 3. Results and Discussion

#### 3.1. Effects of Preheating Parameters on the Compressive Strength of Preheated HVTMP

The effects of preheating temperature and time on the compressive strength of preheated HVTMP are shown in Fig. 2. It could be seen from Fig. 2(a) that as the preheating temperature increased, the compressive strength of preheated HVTMP was found to increase. This could be explained by the fact that magnetite and titanomagnetite in the HVTM were oxidized to hematite and titanohematite, meanwhile, hematite and solid solutions microcrystals formed. The increase of preheating temperature could promote the oxidation reactions, enhancing the compressive strength of preheated pellets. When preheated at 900°C, the compressive strength of preheated pellets was 448 N, exceeding 400 N.\(^{24}\) Figure 2(b) showed that the compressive strength of preheated pellets increased quickly when the preheating time increased from 2 to 10 min, with only a small additional increase in the preheating time range of 10 to 14 min.

#### 3.2. Effect of Preheating Temperature on the Characteristics of Roasted HVTMP

Compressive strength is regarded as one of the quality criteria of roasted HVTMP to assess their suitability as burden materials for gas-based shaft furnace direct reduction process. Figure 3 shows the relationship between the preheating temperature and compressive strength of roasted HVTMP. As shown in Fig. 3, the compressive strength of roasted pellets increased as the preheating temperature increased from 800 to 900°C. At 800°C, the compressive strength of roasted pellets was only 2303 N, while compressive strength with preheating temperature of 900°C was 2945 N, meeting the requirement of shaft furnace
(2,500 N). However, the compressive strength of roasted pellets decreased with the further increase of preheating temperature.

The SEM images and EDS analysis of roasted HVTMP preheated at different temperatures are demonstrated in Fig. 4. When preheated at 800°C, the re-crystallization was very limited. Besides, the distances among the particles were large, and there were little junctions among the particles. When the preheating temperature increased to 850°C, the interior morphology had no noticeable change. The pores were fewer and smaller than those at 800°C. The hematite grains had not connected and many single angular grains were apparent. Some cracks were visible in the surface and there were almost no liquids connecting the block-like structures. It could also be seen that, although some hematite re-crystallization had occurred, strengthening of the pellets could not be promoted effectively.

When the preheating temperature increased to 900°C, hematite grain growth took place throughout the pellet. The predominant crystalline phase was hematite (Point 1) with a little Cr, V, and Ti, and the grains were round and closely connected with each other. The hematite grains had become larger and brighter, crystal bridge connections had fully developed, inter-particle gaps decreased, and there were fewer voids and cracks among the particles. Hematite re-crystallization had completed and become continuous, forming a compact structure intermingled with other mineral grains. In addition, appropriate amount of liquid phases, which affected the improvement of microstructure, were also beneficial to the increase of the compressive strength of HVTMP. According to previous study,\textsuperscript{34)} the equilibrium amount of point defect ($n$) in solid at a specific temperature $T$ can be expressed as follows:

$$n = N \cdot \exp\left(\frac{-E}{kT}\right) \quad \text{.......................... (3)}$$

where $N$ is the total amount of lattice points, $E$ is the Gibbs energy of defect formation, and $k$ is the Boltzmann constant. It shows that the equilibrium amount of point defect increases with the increase of preheating temperature, which changes the cell dimensions and shift of peak positions.\textsuperscript{35)} Therefore, the HVTMP are well-consolidated and bonded, leading to the observed increase in the compressive strength in this study.

However, when the preheating temperature further increased to 950°C, the hematite grains were connected and the interior morphology had noticeable change. The pores were fewer and smaller than those at 900°C. The hematite grains had become larger and brighter, crystal bridge connections had fully developed, inter-particle gaps decreased, and there were fewer voids and cracks among the particles. Hematite re-crystallization had completed and become continuous, forming a compact structure intermingled with other mineral grains. In addition, appropriate amount of liquid phases, which affected the improvement of microstructure, were also beneficial to the increase of the compressive strength of HVTMP.
increased to 950°C, a compact layer quickly formed and residual magnetite in the center was difficult to oxidize completely. If these pellets were roasted at a high temperature, low melting point phases (such as Point 3) formed, resulting in low compressive strength of roasted HVTMP. Figure 5 presents the valuable element distribution of HVTMP when preheated at 900°C. It was found that the elements of Fe and O were relatively more concentrated, while V and Cr were more dispersed.

The phase composition of roasted HVTMP when preheated at 900°C was investigated by XRD and shown in Fig. 6. It could be found that the major phases are hematite (Fe₂O₃) and solid solutions (Fe₉TiO₁₅, (Fe₀·₆Cr₀·₄)₂O₃, Fe₀·₇Cr₁·₃O₃, and (Cr₀·₁₅V₀·₈₅)₂O₃). On one hand, after oxidation roasting of HVTMP, most of Fe connected with O and existed in the form of iron oxide (Fe₂O₃) through the oxidation reaction of Fe₃O₄. The V connected with Cr and existed in the form of V–Cr solid solution (Cr₀·₁₅V₀·₈₅)₂O₃ through the solid solution reaction between V₂O₃ and Cr₂O₃; a small amount of Fe connected with Cr and existed in the form of Fe–Cr solid solutions ((Fe₀·₆Cr₀·₄)₂O₃ and Fe₀·₇Cr₁·₃O₃) through the solid solution reaction between Fe₂O₃ and Cr₂O₃. On the other hand, the content of total Fe in HVTMP was high (54.41 wt%); however, the contents of V and Cr were low (only 0.34 wt% and 1.01 wt%, respectively). Therefore, the elements of Fe and O were relatively more concentrated, while V and Cr were more dispersed.

3.3. Effect of Preheating Time on the Characteristics of Roasted HVTMP

The results concerning the effect of preheating time on the compressive strength of roasted HVTMP are demonstrated in Fig. 7. It showed that the compressive strength of roasted HVTMP increased from 2 348 to 2 945 N as the preheating time increased from 5 to 10 min. However, the compressive strength increased less when the preheating time was further increased to 15 or 20 min.
strength increased very slowly with the further increase of preheating time.

In order to understand the morphology changes of roasted HVTMP at different preheating times, pellets were subjected to SEM observation of the cut and polished surfaces. The results are shown in Fig. 8. When the pellets were preheated at 5 min, hematite re-crystallization was insufficient and an extended range of connected crystals did not form, meanwhile, the inner structures were loose, resulting in relatively low compressive strength. At 10 min, hematite re-crystallization had been promoted, and the porosity decreased. There was an increase in the number and area of connections among grains, resulting in a more dense structure and the enhancement in the compressive strength. At 15 min, the shrinkage of grain pores, hematite re-crystallization, and poly-crystallization had improved the compressive strength progressively. As the preheating time further increased, the increasing volume fractions of liquid phases and the mosaic distributions of mineral phases had created a well-connected structure. The hematite grains had crystalized, agglomerated and grown into larger particles, and had fully connected with each other.

3.4. Reduction Behavior of HVTMP Preheated at Different Conditions

In the production process of HVTMP, the preheating temperature and time are important factors that affect subsequent gas-based direct reduction process. In order to investigate the effects of preheating temperature and time of HVTMP on its reduction degree, phase composition, and reduction swelling, the HVTMP prepared at different preheating conditions were reduced subsequently with simulated shaft furnace gas compositions of HYL-III and the results are shown as follows.

3.4.1. Reduction Degree

The reduction degree of HVTMP preheated at different conditions is presented in Fig. 9. It could be seen from

Fig. 8. SEM images of roasted HVTMP preheated at different times. (preheating temperature: 900°C, roasting temperature: 1200°C, roasting time: 20 min). (a) 5 min; (b) 10 min; (c) 15 min; (d) 20 min; (e) 25 min.

Fig. 9. Effects of preheating parameters of HVTMP on its reduction degree. (a) preheating temperature (preheating time: 10 min); (b) preheating time (preheating temperature: 900°C).
Fig. 9(a) that the reduction rate increased slightly with the increase of preheating temperature, however, from 900 to 1,000°C, the reduction rate decreased. As discussed in section 3.2, when HVTMP was preheated at 800°C, the oxidation reactions were limited, resulting in slow reduction rate in subsequent reduction process. With the preheating temperature increased, the oxidation reactions became quick and hematite re-crystallization had been improved, which were beneficial to subsequent reduction process and increased the reduction rate. However, as the preheating temperature further increased, a compact layer quickly formed and residual magnetite in the pellet center was difficult to oxidize completely, besides, some iron oxides remained in the stable slag phases, making subsequent reduction process more difficult and decreasing the reduction rate. Figure 9(b) showed that the increase of preheating time of HVTMP promoted its reduction process. At given reduction time, the higher preheating time of HVTMP, the higher reduction rate and final reduction degree were measured.

3.4.2. Phase Composition

The phase compositions of reduced HVTMP were determined by XRD analysis as shown in Fig. 10. These patterns showed the same final phase compositions but with progressive changes in the intensities of peaks with different preheating conditions of HVTMP, meaning that preheating temperature and time had slight effect on the final phase compositions of reduced HVTMP. Under the same reduction regime, when HVTMP was preheated at 800°C, the peaks of metallic iron and rutile were observed and their intensities increased slightly with the increase of preheating temperature. Also, as the preheating time increased, it was found that the amount of metallic iron gradually increased. It should be noted that other valuable elements, i.e., vanadium and chromium, were not detected by XRD because of the low content of these elements, which will be discussed in our further study. In addition, Fig. 11 presents the valuable element distribution of reduced HVTMP preheated at 900°C.

In order to investigate the reason for the dependence of the phase compositions of roasted HVTMP on the reduced HVTMP, the roasted HVTMP were analyzed by XRD (Fig. 12). As indicated in Fig. 12, the compositions were complex and the major phases were hematite and solid solutions (Fe_{0.6}Cr_{0.4}O_3, Fe_{0.7}Cr_{1.3}O_3, and (Cr_{0.15}V_{0.85})_2O_3). Increasing preheating temperature and time had little effect on the phase compositions of roasted HVTMP, but had progressive changes in the intensities of peaks with different preheating conditions. Therefore, in subsequent reduction process, the reduced HVTMP also showed the same final phase compositions.

3.4.3. Reduction Swelling Behavior and Mechanism

It is known that volume swelling of the reduced pellets is a common phenomenon in the gas-based shaft furnace operation. A volume increase below 20% is considered normal. The effects of preheating temperature and time of HVTMP on its subsequent reduction swelling index are shown in Fig. 13. Figure 13(a) showed that the reduction swelling index first decreased and then increased with the increase of preheating temperature. When HVTMP was preheated at 800°C, the reduction swelling index was higher than the normal swelling index. However, when the preheating temperature increased to 900°C, the reduction swelling index decreased to less than 20%. Figure 13(b) showed that an increase in the preheating time of HVTMP decreased its reduction swelling index. It indicated that the increase of preheating time of HVTMP suppressed its reduction swelling, which was consistent with our previous study that an increase in roasting time of HVTMP considerably decreased the reduction swelling index.33)

The reduced HVTMP were subsequent broken to be examined by SEM to investigate difference of reduction swelling and the results are shown in Figs. 14 and 15. In Fig. 14(a), when the preheating temperature was 800°C, it could be found that a large number of iron whiskers formed, which changed the morphology and made the product iron porous and caused high reduction swelling. With the increase of preheating temperature, the iron whiskers tended to be massive and clustered together, making the decrease of reduction swelling. However, some iron whiskers could be seen and the morphology became porous when the preheating temperature further increased to 1,000°C. The changes in

![Fig. 10. XRD analysis of the reduced HVTMP preheated at different conditions. (a) preheating temperature (preheating time: 10 min); (b) preheating time (preheating temperature: 900°C).](image-url)
the morphology were consistent with the results in Fig. 13(a).

Figure 15 shows the morphology changes of reduced HVTMP when the preheating time increased from 5 to 25 min. In the SEM image of Fig. 15(a), when the preheating time was 5 min, it showed that the dense iron whiskers formed on the surface and the morphology was porous. However, only a few iron whiskers could be seen in Fig. 15(b) when the preheating time increased from 5 to 15 min. Figure 15(c) showed that the morphology became more compact and the iron whiskers clustered together when the preheating time was further increased to 25 min. This phenomenon explains well that the increase of preheating time of HVTMP suppressed its reduction swelling. Besides, it was also found that the reduction swelling of reduced HVTMP showed an opposite tendency on the compressive strength of roasted HVTMP, this phenomenon could be explained as follows. When the roasted HVTMP have high compressive strength, the inner structures are compact and the porosities are low. All these inhibit the growth of iron whiskers and result in low reduction swelling. Apart from the influence of preheating temperature and time exerted on whiskers to the iron oxide system, according to our previous study,\textsuperscript{33} it could be known that with the increase of roasting temperature and time, the size and number of iron whiskers decreased, which suppressed the reduction swelling. Besides, the amount and size of iron whiskers increased with the increase of reduction temperature; however, it decreased with the increase of H\textsubscript{2} content.

Based on the results obtained above, the reduction swelling mechanism of HVTMP with different preheating condi-
tions was described by a schematic illustration shown in Fig. 16. In Fig. 16(a), when the HVTMP was preheated at 800°C, a large amount of iron whiskers could be seen in the reduced HVTMP, resulting in the severest reduction swelling. When the preheating temperature increased to 900°C, the reduction swelling decreased because the iron whiskers became clustered, in which the iron whiskers were short in length. Besides, some reduced iron formed layers on the surface of particles and decreased the reduction swelling. However, at 1000°C, more iron whiskers formed on the surface than that at 900°C, explaining the increase of reduction swelling.

As discussed in the effect of preheating temperature of HVTMP on its reduction swelling, the number of iron whiskers is the key factor influencing reduction swelling. Figure 16(b) showed that when the preheating time was 5 min, a large number of iron whiskers formed, which separated the particles and changed the morphology, causing high reduction swelling. When the preheating time increased to 15 min, few iron whiskers formed on the surface of particles and iron whiskers clustered. At 25 min, almost no iron whiskers could be observed and made the reduced iron become a dense layer, which caused the reduction swelling to decrease.

From the above results, it could be found that different preheating temperatures and times of HVTMP could result in different properties, such as oxidization, crystallization, distribution of slag phases, and compressive strength, etc. These differences will affect subsequent gas-based direct
The following conclusions could be drawn: simulated shaft furnace gases were carried out in this study.

4. Conclusions

(1) The compressive strength of preheated and roasted HVTMP increased with the increase of preheating temperature and time to some extent. The compressive strength of roasted HVTMP had great relationship with the inner microstructures.

(2) Increasing preheating temperature and time of HVTMP accelerated its subsequent reduction process, however, from 900 to 1 000°C, the reduction rate decreased. The preheating temperature and time of HVTMP had little effect on the final phase compositions of reduced HVTMP but with progressive changes in the intensities of peaks. The main phase compositions of reduced HVTMP were metallic iron and rutile.

(3) The reduction swelling index decreased with the increase of preheating temperature and time of HVTMP. However, a further increase in preheating temperature (from 900 to 1 000°C) increased the reduction swelling index due to the formation of iron whiskers on the surface. A schematic illustration had been formulated to describe the effects of preheating temperature and time of HVTMP on its subsequent reduction swelling.

(4) In the practical production process of HVTMP, the preheating system should be optimized to meet the requirements of compressive strength and reduction swelling of HVTMP smelting in the gas-based shaft furnace.

Acknowledgement

This work is financially supported by National Natural Science Foundation of China (Grant No. 51574067).

REFERENCES