



Effect of Density on the Reduction of Fe_2O_3 Pellets by H_2 -CO Mixtures

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Abstract

This study aims to find how density affects the reduction extent and reduction rate. H₂-CO gas mixture is used as reducing agent. Five groups of different density pellets were reduced at four different temperatures. Light optical microscope (LOM) and scanning electron microscope with energy dispersive X-ray spectroscopy (SEM-EDS) used to detect completely and partially reduced pellets to investigate how density affects the reduction mechanisms. Results illustrate that density affects reduction extent and reduction rate a lot. However, when reaction temperature is 1123 K, density has less influence on reduction extent. The carbon deposition occurred for high density pellets at 973 K and 1023 K. The reduction process cannot be described by a single rate controlling step. Reduced layer is denser compared with unreduced layer. Reaction at initial stages goes much faster than later stages.

Key words: Hematite, direct reduction, density, carbon deposition, reduction mechanism.

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1. Introduction

1.1 Direct reduced iron

Direct reduced iron (DRI) is the product of reduction iron ores (lumps, pellets or fines) in solid state by gas or coal reducing agents. The reaction temperature range is 973 K to 1423 K. MIDREX and HYL process are two main DRI technologies for gas-based direct reduction (DR). DRI is used as iron feedstock of electric arc furnace (EAF) in addition to scrap and pig iron. It has various advantages: the reducing agent is less expensive than coke and the product contains low carbon. Meanwhile CO₂ emission is decreased. The cost for DR process is lower than blast furnace.

Reduction of hematite by H₂ can occur in two (above 843 K) or three steps (under 843 K), the following equations [1]:



1.2 Purpose

This thesis is work on how different densities affect the reduction rate and reduction extent at different temperatures.

The effect of density of the pellet on degree of reduction and carbon deposition in H₂-CO mixture is experimentally studied at different temperatures. The mechanisms of reduction are studied in partially and completely reduced pellets using light optical microscope (LOM) and scanning electron microscope equipped with energy dispersive X-ray spectroscopy (SEM-EDS).

2. Literature review

Pineau et al. [1, 2] investigated the kinetics of reduction of hematite and magnetite at low temperatures by H₂ and CO. In their work, reduction of hematite and magnetite in the temperature range of 493—953 K and 483—1223 K was mainly focused. They found out that magnetite reduction route depends on the reaction temperature. Moreover, Fe₃O₄ reduced by H₂, the activation energy decreased from 88 to 39kJ/mol when temperature changed at 693 K. This could be the annealing effect on the magnetite defects. Reduction by H₂ has higher rate compared with CO. However, when the hematite reduction temperature was higher than 693 K and H₂ was used, compact iron layer was formed. When CO gas was used, it did not show this compact layer. In situ XRD indicated that stoichiometric FeO is intermediate product of reduction of Fe₃O₄ to Fe, between 663 K and 843 K and non-stoichiometric wüstite was formed upper than 843 K. Fe₃O₄ produced from hematite reduction at 1473 K has a minimum reduction rate at 1033 K. This may be due to sintered reduction product which was observed by SEM.

EL-Geassy [3] has studied reduction of dense Fe₂O₃ briquettes at 873 K to 1323 K, by using hydrogen, carbon monoxide and H₂-CO mixture as reducing agent. In the experiments completely and partially reduced samples were used to observe the phase change and study the mechanism by microscope, carbon analysis and X-ray diffraction (XRD). The results show that reduction rate was highest for H₂ at early stages of reaction. For H₂ and CO gas mixture, as CO content increased the reduction rate decreased. At the later stages of reaction, for hydrogen and hydrogen-rich gas mixtures, reduction rate slowed down at 1173 K to 1223 K. This may be due to phase transformation and/or sintering of the iron phase. However, this phenomenon could be removed by using carbon monoxide and carbon monoxide-rich gas mixtures. Because of the side reactions due to carbon deposition ($2\text{CO} = \text{C} + \text{CO}_2$; $\text{C} + 2\text{FeO} = 2\text{Fe} + \text{CO}_2$), concentration of CO₂ at Fe/FeO interface will increase. Comparison of initial and later stages of reduction indicates that in H₂-CO gas mixtures CO has negative and positive effects on reduction.

In the work of pure hematite pellets reduction with CO-H₂ mixtures by Kazemi [4], different temperatures, gas flow rates and gas compositions were applied. A certain gas

mixture was studied on how flow rate (1, 1.5 and 2 L/min) will affect the reduction. Increased flow rate increased reaction rate. But it has slight increase from 1.5L/min to 2L/min. Two proportions of mixtures $H_2/CO= 1$ and 1.5, have shown almost same reduction curves. As increased temperature the reduction rate increased. Meanwhile increase of flow rate decreased this affect. The pellets had porosities between 30 to 50 percent and no carbon deposition occurred.

Szekely et al. [5] used hydrogen and carbon monoxide mixtures to reduce hematite disks for developing a mathematical model. In the investigation, the reduction was based on shrinking core model in the temperature range of 1073 K to 1173 K. For the case they studied, the model was in good agreement with experimental results at the same gas composition and temperature. Also, the reduction by hydrogen was faster than carbon monoxide for both predicted and experimental results. Along with carbon monoxide content increase, reduction required more time. This study focused on Szekely and El-Tawil's experimental condition. The kinetic parameters in the model need to be readjusted to different systems.

K.Higuchi and R.H.Heerema [6] have researched how the sintering temperature (T_s) will affect the pure hematite compacts by using $CO-CO_2-N_2$ mixture as reducing agent. They focused on temperature range from 1373 K to 1673 K. They used optical microscopy, XRD and SEM to analyze the samples before and after reduction. When temperature was over 1643 K, magnetite formation and re-oxidation back to hematite caused the hematite grains to become larger and more irregular. In addition, due to the phase transition, fine cracks generated along grain boundaries and coarse pores were formed. Reduction temperature and microstructure was the key factor affect the reduction process.

M. Bahgat and M.H. Khedr [7] have investigated the reduction kinetics, magnetic and morphological behavior of the octahedral shape of 1 gram magnetite single crystals reduced at 1173-1373 K by hydrogen. XRD, SEM and reflected light microscope were used to test the results. The reduction rate increased with increasing temperature. However, the reduction extent was 83% and 89% at 1173 K and 1223 K, respectively. The results showed that solid-state diffusion dominated the reduction rate. Meanwhile, the magnetization value increased to 132.1emu/g from 114.1emu/g as temperature

increased. Magnetic properties were determined by morphology which was proved by partially reduced samples.

W.K. Jozwiak et al. [8] have studied reduction behavior of iron oxides (hematite- Fe_2O_3 , magnetite- Fe_3O_4 , wüstite- FeO) and iron oxy-hydroxides (goethite- FeOOH , ferrihydrite- $\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$). They dehydrated iron oxy-hydroxides in the hydrogen and carbon monoxide atmosphere at a low-temperature (<573 K). They used thermo-gravimetric, differential temperature analysis (TG-DTA-MS) and 'in situ' XRD to study the reduction behavior. Due to the thermodynamic issue, when temperature overlapped 843 K, three step mechanisms were usually assumed to be the reaction route. At different reduction temperatures, some disproportionation reaction occurred. Below 843 K, $4\text{FeO} = \text{Fe}_3\text{O}_4 + \text{Fe}$ was a forward reaction, meanwhile above 843 K, backward reaction was controlling. The disproportionation reaction was independent of atmosphere. The FeO disproportionation at 473 K occurred much easier than FeO reduction by hydrogen above 623 K and it did not consume hydrogen. In this disproportionation reaction, the oxygen sub-lattice did not change during the phase transformation. However, iron phase formation needed to reach the temperature which activated diffusion through inter phase FeO/ Fe_3O_4 . The hematite reduction to metallic iron with H_2 could happen even below 653 K, if temperature programmed reduction (TPR) meets conditions for heating rate and hydrogen flow rate. In spite of the results, reduction condition, particle size and crystallinity still affect the reduction to a high extent.

3. Experimental method

3.1 Equipment

Figure 1 shows the real experimental equipment and the schematic drawing of set-up. The equipment is used for hematite pellets reduction. The reducing agent is H_2 -CO gas mixture, with $\text{H}_2/\text{CO} = 1.5$ and for all reduction tests is fixed flow rate equal to 0.75 L/min is applied. From the top, there is a Sartorius Precision balance (AX4204). It could record the weight at any time since the pellet is put into the quartz sample holder. The

balance is fixed in the sealed Plexiglas box, and the box is filled with constant argon flow (0.2L/min) to protect the balance from reacting gases. The balance is connected to the computer in order to record the data.

The lifting device is used to move the pellets from cooling chamber to the temperature zone of the furnace. There are two k-type thermocouples used in set-up. One always follows the temperature of the pellet and the other one detects furnace temperature.

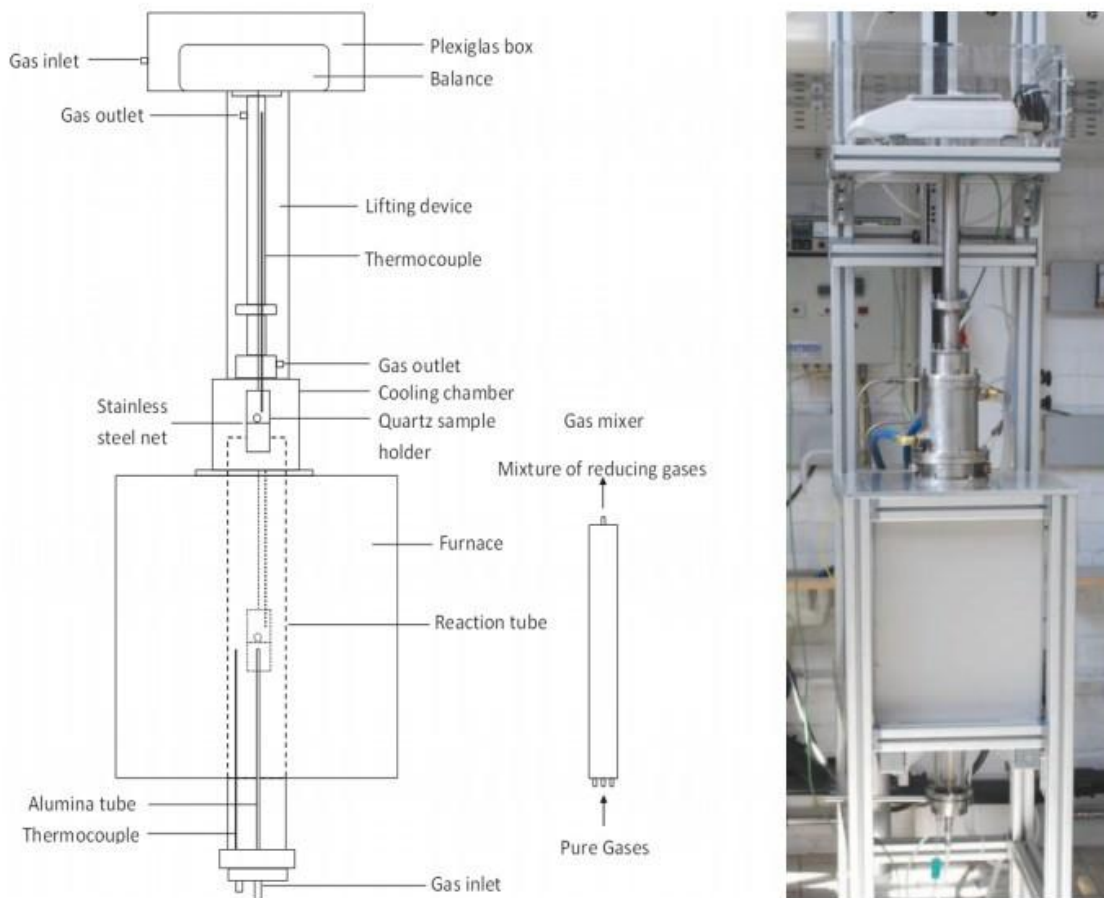


Figure.1. Experimental equipment [4]

The quartz tube is used to hold the pellet. It has 24 millimeter diameter inside. Height is 105 millimeter. There are 12 holes homogeneously aligned around the tube, 50 millimeter from the bottom. Thin stainless steel wire is used to make a mesh to hold the pellet in the center of the tube. At five millimeter from the top of the tube, Kanthal wire is used to hook the sample holder with lifting device.

The furnace has a maximum heating temperature of 1373 K. Mixed reducing gas will fill in from the bottom via an alumina tube, which is close to the sample in order to eliminate mass transfer in gas phase around the pellet. Before the reducing gas filled in, there is a gas mixer, which could mix H₂ and CO homogeneously.

3.2 Sample preparation

The pellets have 99.5 percent purity of hematite and are supplied by Fisher Scientific. Pellets are made of hematite fine powder blended with water. The pellets were made as spherical and uniform as possible. First the pellets were dried at room temperature and then they were put into oven at 363 K for 12 hours. After drying, the pellets were sintered at 1173 K, 1223 K, 1273 K and 1323 K for 12 hours with 6 K/min heating rate. Meanwhile, the size of pellets decreased as sintering temperature increased. Figure 2 shows samples after drying and sintering at different temperatures. The color changed gradually from red into gray. The diameter range is between 9.90 and 11.47 millimeter. Mean value is 10.77 millimeter. Thus, four groups of samples with different porosity were made. Plus one more group which was sintered at 1223 K for 9 hours. These pellets have 11 to 14.5 millimeter diameter and 30 to 50 % porosity. Hence, this group pellets has an 18.38% longer diameter than the four groups pellets.



(a)

(b)

(c)

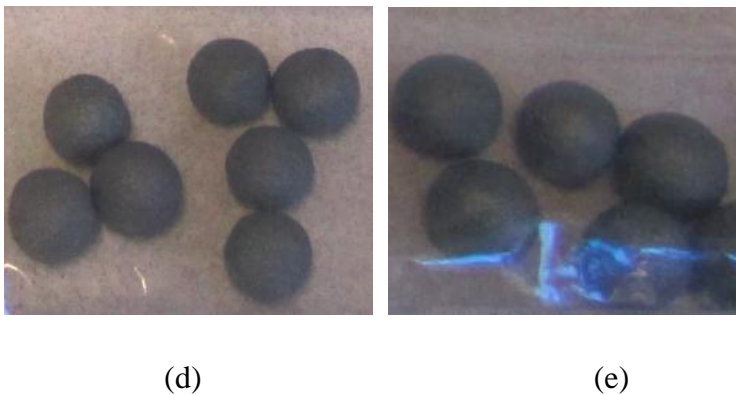


Figure.2. Pellets dried and sintered at 363 K (a), 1173 K (b), 1223 K (c), 1273 K (d) and 1323 K (e) from left to right.

3.3 Experimental procedure

This experimental procedure was followed for each experiment. Firstly, the pellets were put in the center of the tube net and the weight was checked. Then the pellets were moved into the cooling chamber and the furnace was closed and sealed. Argon with high flow rate (1 L/min) was passed through the set-up to eliminate air and heating was started with 6 K/min. When the furnace temperature reached to the reaction temperature and became stable, the gas was changed to H₂-CO gas mixture with H₂/CO = 1.5 and 0.75 L/min flow rate instead of argon. Ten minutes later, the pellets were moved down to the temperature zone and the weight was recorded. When reaction proceeds, the weight decreases. When weight became stable the pellet was moved up and cooled down in cooling chamber. At the same time, reducing gas was changed by high flow rate argon. After quenching the pellet, pellets were kept in desiccator and some samples were prepared for further study by LOM and SEM.

3.4 Calibration curves

Recorded data need to be calibrated due to other factors except reduction which affect the weight change. For this reason baseline tests were carried out. Weight change of an

alumina cylinder, with weight close to the pellets, was recorded at same temperatures, gas flow rate and gas composition as reduction tests. In this project, mixed reaction gas with 0.75 liters/minute flow rate (0.45L/min H₂, 0.3L/min CO) were used at 973 K, 1023 K, 1073 K, and 1123 K.

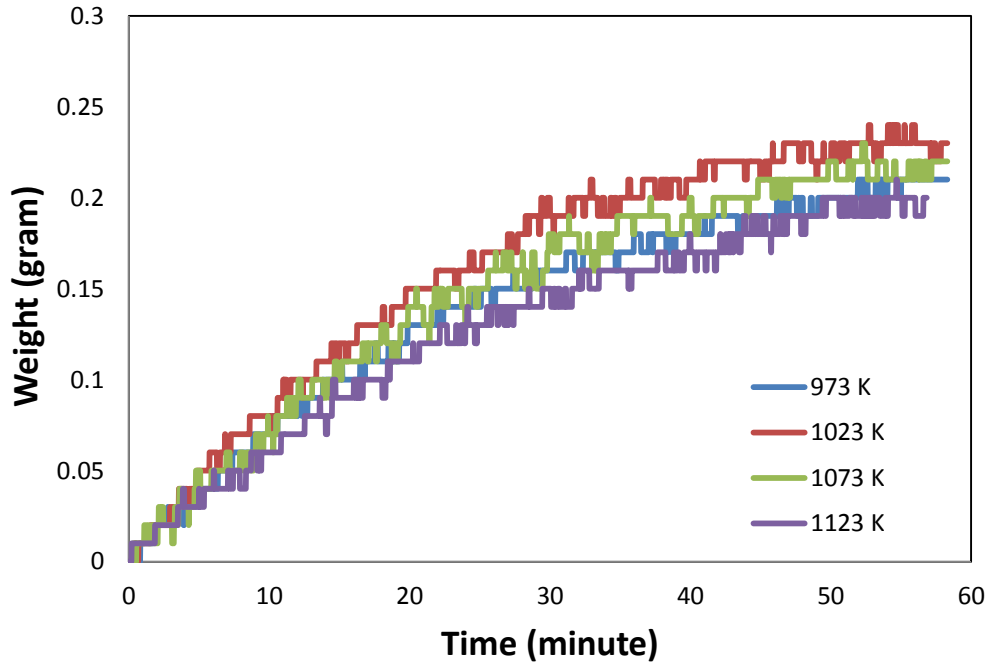


Figure.3. Calibration curves of alumina at temperature 973 K, 1023 K, 1073 K, and 1123 K. flow rate (F_R) = 0.75 L/min.

Figure 3 shows the calibration curves, the largest deviation in weight was close to 0.25 grams. As time going, the deviation became stable.

4. Results and discussions

4.1 Data analysis

Reduction extent is calculated by this equation:

$$R\% = \frac{(W_1 - W_2)}{O\% \times W_1} \times 100$$

where R% is reduction extent, W1 is initial pellet weight, W2 is final pellet weight after reduction, and O% is total oxygen content in the pellets which is equal to 30 percent for pure hematite.

Table 1 shows average densities for different sintering conditions. Porosity value decreased gradually from 1173 K sintered pellets to 1323 K sintered pellets except the pellets which were sintered for 9 hours at 1223 K.

Table 1. Sintering condition vs. density

Sintering conditions	Average density g/cm ³ (Porosity %)
1223 K, 9 hours	3.209 (38.79)
1173 K, 12 hours	3.742 (28.64)
1223 K, 12 hours	4.133 (21.15)
1273 K, 12 hours	4.539 (13.58)
1323 K, 12 hours	4.796 (8.50)

4.2 Reaction rate and reduction extent

All the experiments used the same H₂-CO reducing gas mixture (H₂/CO=1.5) and same flow rate (F_R) 0.75 L/min. Reduction temperature (T_R) 973 K, 1023 K, 1073 K and 1123 K are used to run experiments.

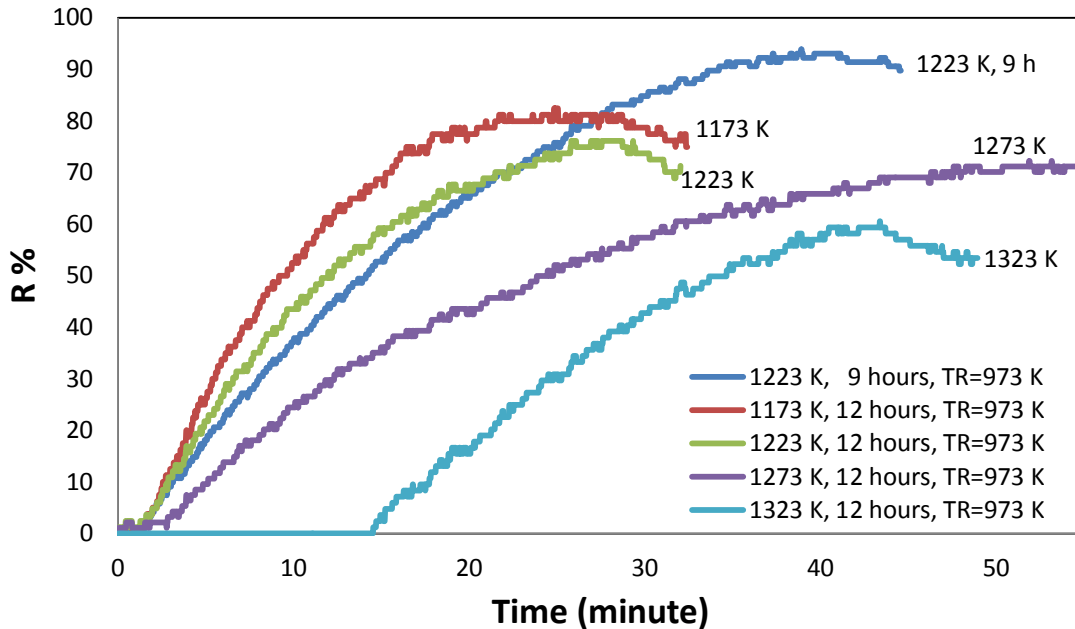


Figure.4. Reduction extent vs. time, for different T_S pellets. At $T_R = 973$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

At 973 K reduction temperature, figure 4, pellets with lower density have higher reduction extent and shorter reduction time. Except 1223 K, 9 hours sintered pellet, which has the lowest density and largest volume. Diffusion of reacting gas and products is faster in pellets with high porosity. For 1323 K sintered pellet, reduction started after 14 minutes. This time was longer comparing with low density pellets. Meanwhile, reduction of this high density pellet stopped at 60.50 percent reduction extent. However, 1273 K and 1323 K sintered pellets reacted much slower compared with the rest of pellets, especially at the very beginning of the reduction. What is more, the weight increased after the reduction stopped. This is because carbon deposition occurred.

Reduction extents vs. time were plotted in figures 5-7 for $T_R = 1023$ K, 1073 K and 1123 K. In figure 5, $T_R = 1023$ K, reduction degree increased when density decreased.

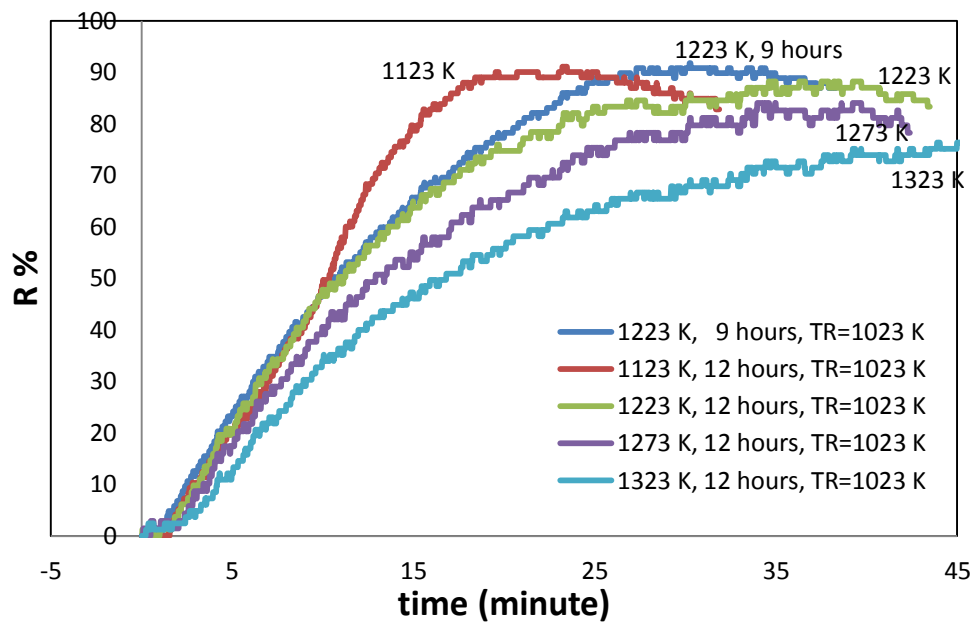


Figure.5. Reduction extent versus time, for different T_S pellets. At $T_R = 1023$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

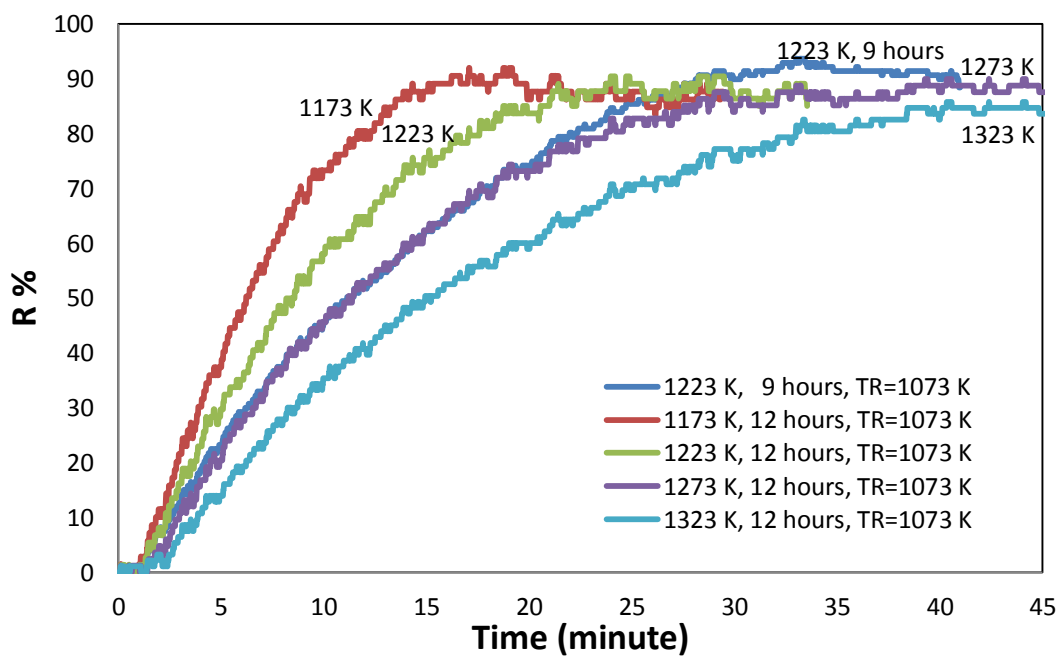


Figure.6. Reduction extent versus time, for different T_S pellets. At $T_R = 1073$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

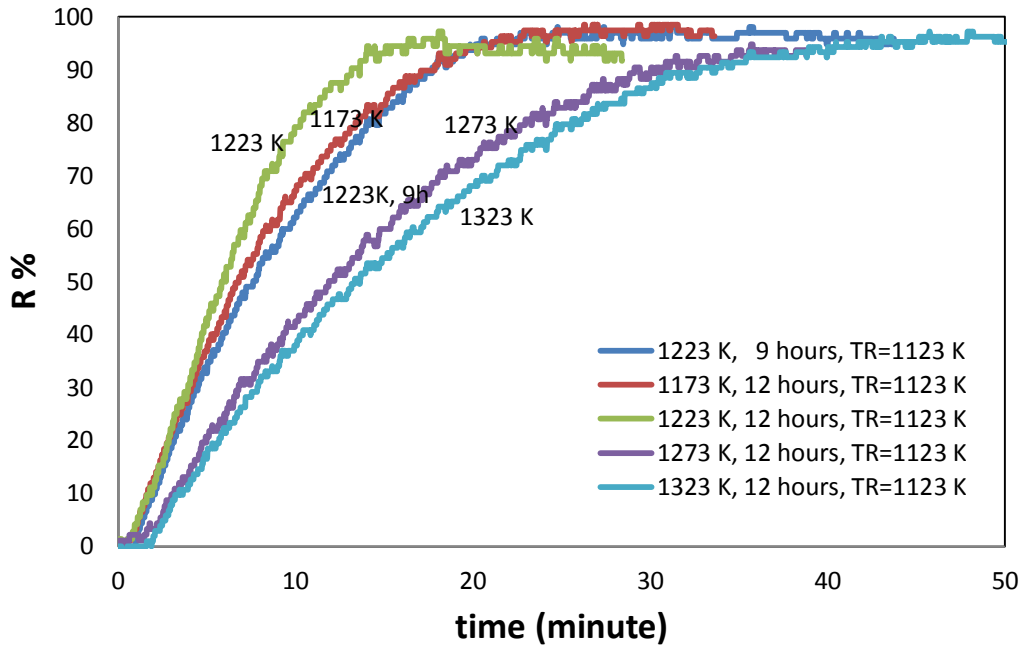


Figure.7. Reduction extent vs. time, for different T_S pellets. At $T_R = 1123$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

In figures 6 and 7, reduction temperatures 1073 K and 1123 K, the reduction extent is close between different densities of pellets. For all the figures, high density pellets (sintered at $T = 1273$ K and 1323 K) need more reduction time and have slow reaction rates. Except reduction curves at 973 K, all the other reduction curves at higher temperatures show that the reaction rate is fast at first 15 minutes of reduction, then the rate slows down until reduction is finished.

All the figures show that the lowest density pellets (sintered at 1223 K, 9 hours) do not have the highest reduction rate. Pellets which were sintered at 1173 K and 1223 K for 12 hours have a higher reduction rate. For the lowest density pellets, the diameter is 18.38% bigger. Thus, the reduction rate may be influenced by the size. However, the reduction extent is highest for lowest density pellets (sintered at 1223 K, 9 hours) at all reduction temperatures. Pellets with higher porosity (1173 K, 1123 K sintered, 12 hours) and small size have a higher reduction rate.

Furthermore, figure 8 shows how the density affects reduction extent.

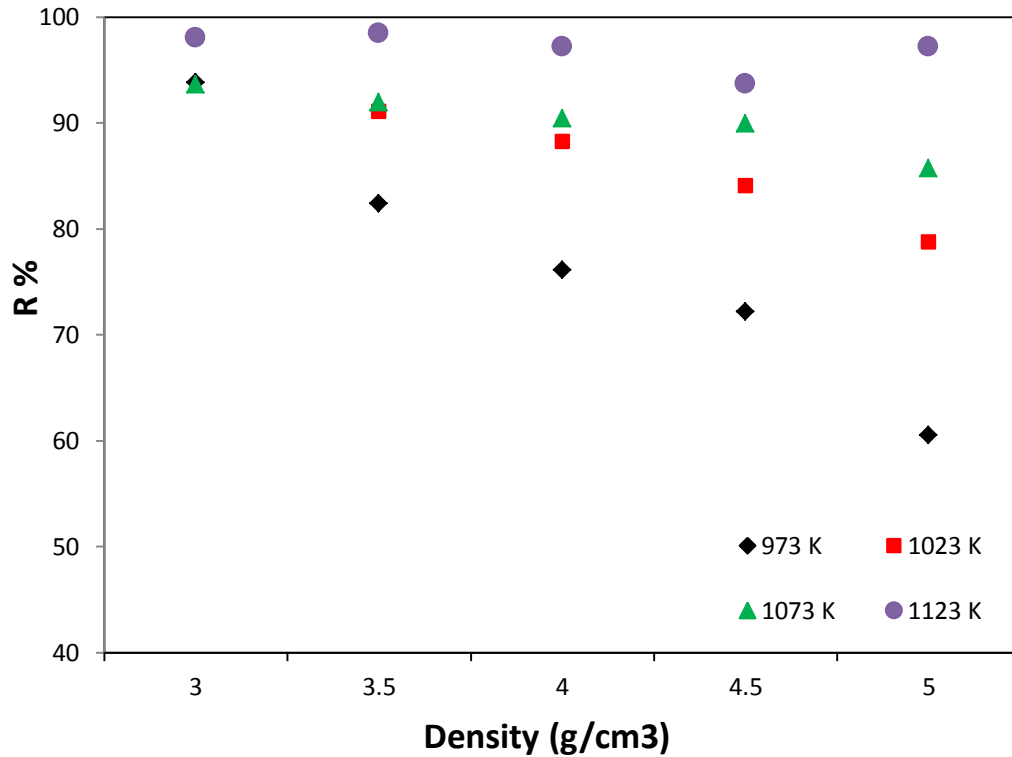


Figure.8. Effect of density on reduction extent.

Figure 8 indicates that density has an important role on reduction extent when reaction temperature is less or equal to 1073 K. When temperature reaches to 1123 K, density has less influence on reduction extent. Temperature and density have a synergic effect on reduction extent.

Figures 9 and 10 show two different density pellets reduced at different temperatures. Two reduction curves indicate that higher density has more influence on reduction extent for different reaction temperatures.

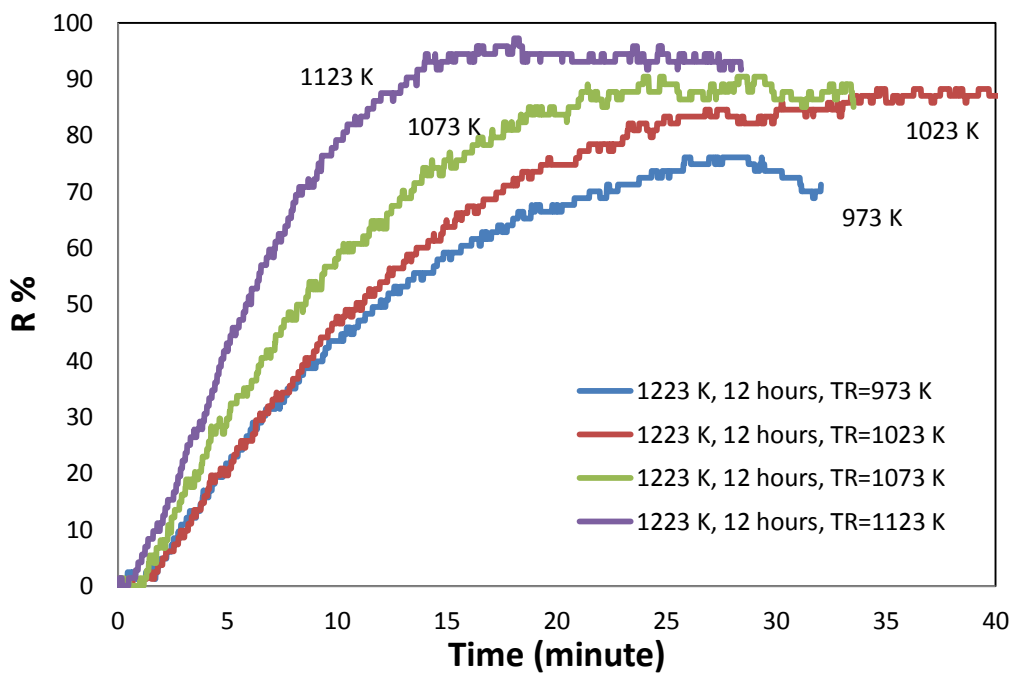


Figure.9. Reduction extent vs. time, $T_S = 1223$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

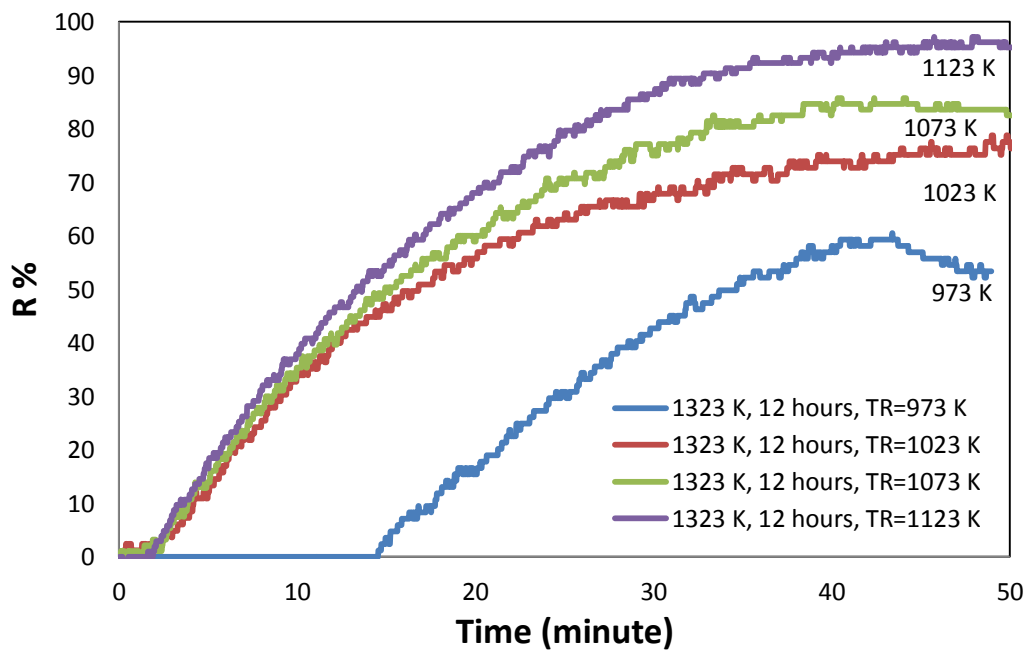


Figure.10. Reduction extent vs. time, $T_S = 1323$ K, $F_R = 0.75$ L/min, $H_2/CO = 1.5$.

4.3 Carbon deposition

Carbon layer was observed on the pellets at lower temperatures, 973 K and 1023 K, for higher density pellets.

High density pellets have slow diffusion of reacting and product gases inside the pellets. From the equation: $\text{CO}_2 + \text{C} = 2\text{CO}$, due to slow diffusion, high density pellets have higher probability for carbon deposition. When CO content increases in the outside layer, the above reaction shifts to the left side of the equilibrium equation. Below are few pictures which show pellets with carbon deposition and without carbon deposition.



(a) Little carbon deposition. (b) Carbon deposition. (c) After carbon removal.

Figure.11. (a) $T_S = 1173 \text{ K}$ and $T_R = 1073 \text{ K}$. (b) and (c) are the same pellet, which $T_S = 1273 \text{ K}$ and $T_R = 1023 \text{ K}$.

After carbon removal of pellet (a), picture (c) shows a smooth and metal lustre surface. This phenomenon was seen in all the pellets which were carbon deposition. Pellets without carbon deposition are coarse.

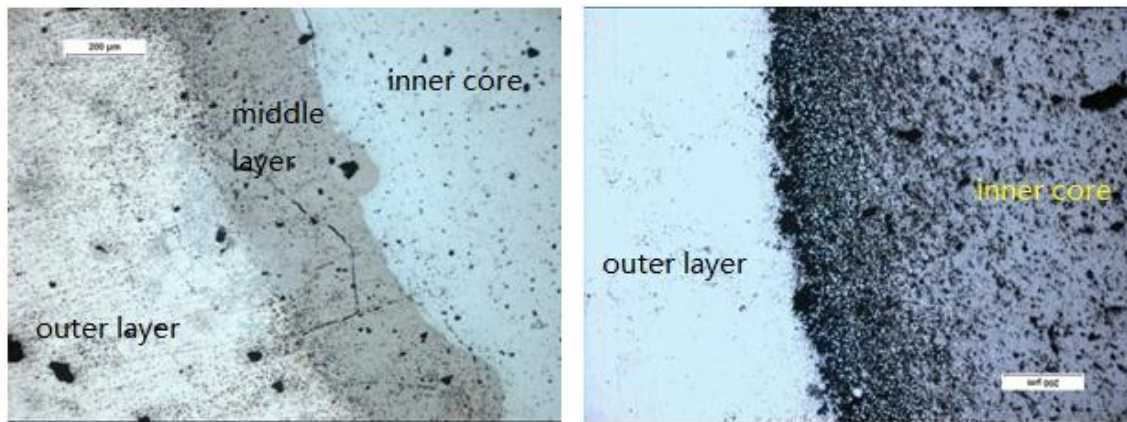
Table below is to show how density affects carbon deposition at different reaction temperatures.

Table 2. Presence of carbon on sample surface after quenching.

Sintering conditions \ Reduction temperatures(K)	1223 K, 9 hours	1173 K, 12 hours	1223 K, 12 hours	1273 K, 12 hours	1323 K, 12 hours
973	None	Little	Little	Existence	Existence
1023	None	None	Little	Existence	Existence
1073	None	Little	Little	Existence	None
1123	Existence	None	Existence	None	Existence

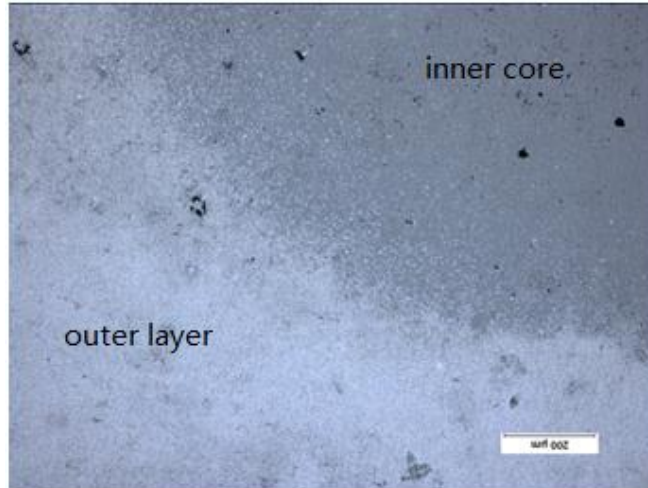
4.4 Reaction mechanisms

Figure 12 (a) and (b) show microstructures of partially reduced samples obtained by light optical microscope. Figure 12 (c) is microstructure of completely reduced pellet.



(a)

(b)



(c)

Figure.12. Microstructure of pellets (a) ($T_S = 1323$ K, $T_R = 973$ K), (b) ($T_S = 1173$, $T_R = 973$ K) and (c) ($T_S = 1323$ K, $T_R = 973$ K).

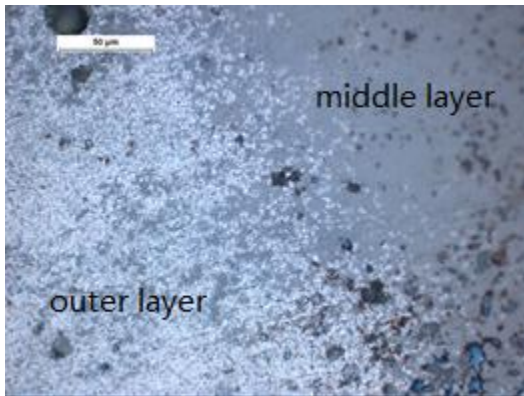
Figure 12 (a) is high density pellet. Three layers were formed. The white color shows iron, grey shows iron oxide and black shows pores. High iron content in outer layer was detected by SEM-EDS. From SEM-EDS results, it can be predicted that inner core is hematite, but further XRD analysis are required to confirm this result.

Figure 12 (b) is low density pellet. It shows no middle layer because of high porosity, which makes diffusion of gases easy. The outside layer has high iron content.

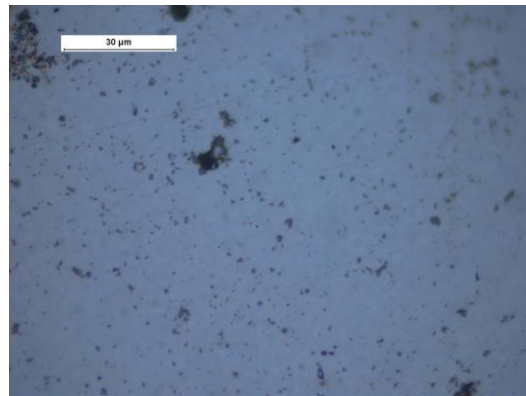
Figure 12 (c) is high density pellet, but reaction was continuous until it stopped. The inner core contains iron oxide and the outer layer has high contents of iron. Reduction extent is only 60.5% at 973 K for this high density pellet and reduction stopped before completion. Carbon analysis result for another pellet with same reduction and sintering conditions, show 2.21%wt content of carbon. Carbon deposition may be one of the reasons to decrease the reduction extent. It may hamper diffusion of reducing and product gases through the pellet.

Pictures of figure 13 are magnified images of the three pellets used in figure 12. All these pellets were reduced at 973 K. Figures 13 (a) and 13 (b) are from a partially reduced

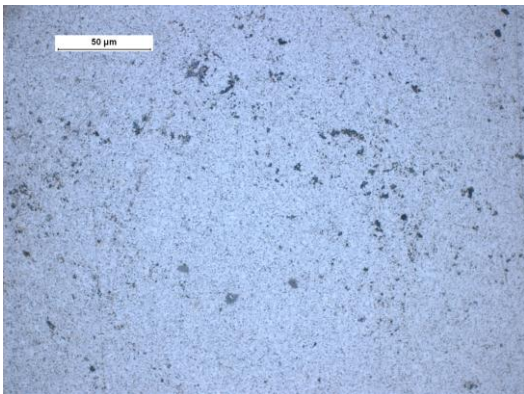
pellet, which was sintered at 1323 K. Figure 13 (a) is from interface of outer layer and middle layer, and 13 (b) is from inner core. Figures 13 (c) and 13 (d) are from partially reduced pellet, which was sintered at 1173 K. Figure 13 (c) is from outer layer and 13 (d) is from inner core. Figures 13 (e) and 13 (f) are completely reduced pellet which was sintered at 1323 K. Figure 13 (e) is from the interface of inter core and outer layer and 13 (f) is from inner core.



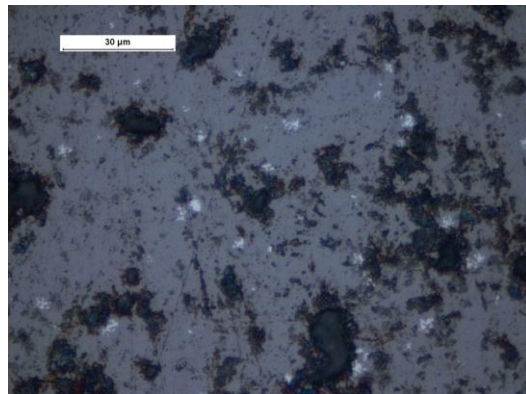
(a)



(b)



(c)



(d)

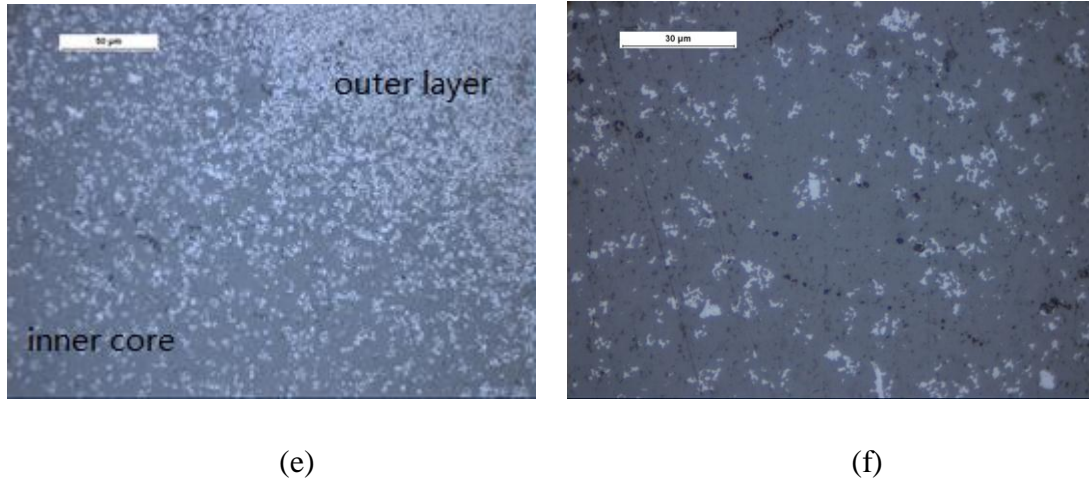
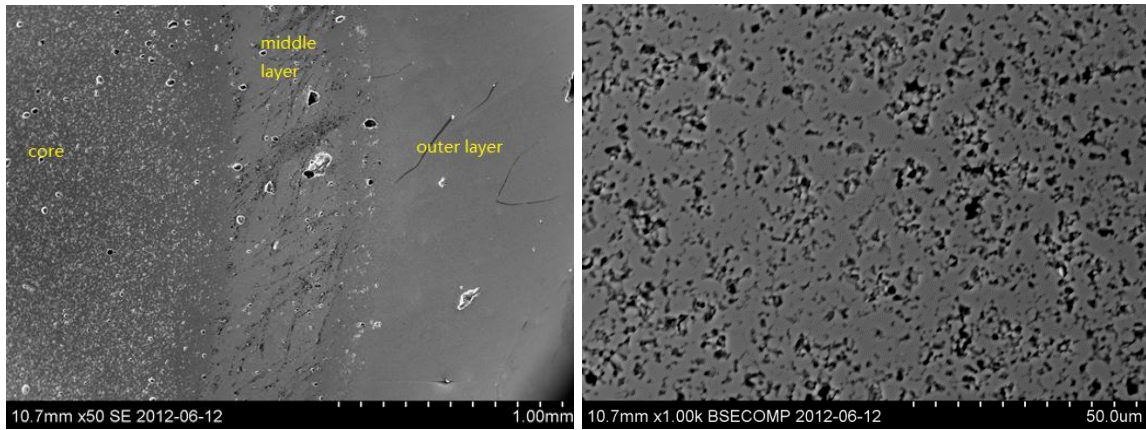


Figure.13. Microstructure of partially reduced pellets (a), (b) ($T_S = 1323\text{ K}$, $T_R = 973\text{ K}$); (c), (d) ($T_S = 1173\text{ K}$, $T_R = 973\text{ K}$) and completely reduced pellet (e), (f) ($T_S = 1323\text{ K}$, $T_R = 973\text{ K}$).

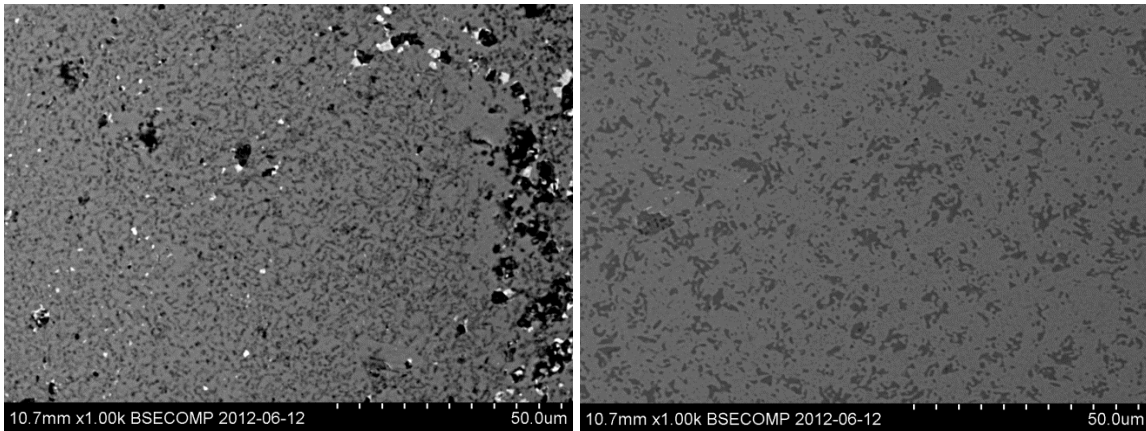
Figure 13 (b), (d), (f) are inner core of each pellet. Figure 13 (b) (partially reduced high density pellet) only shows iron oxide in the core. Meanwhile, 13 (d) (partially reduced low density pellet) and 13 (f) (completely reduced high density pellet) have shown random spots of iron phase. Even in figure 13 (f), the iron phase area is smaller than iron oxide phase, which confirms incomplete reduction in the sample with high density and at low reduction temperature.

Figure 13 (c) is outer layer. After partially reduction, the outer layer has a good reduction result (light area is iron phase) and still lots of pores exist in the iron phase. By contrast, figure 13 (e) (interface of outer layer and inner core) has little pores. Comparing figure 13 (a) and 13 (e) demonstrates that further reduction of pellets formed dense layer.



(a)

(b)



(c)

(d)

Figure.14. SEM observation of partially reduced pellet, $T_S = 1323 \text{ K}$, $T_R = 1123 \text{ K}$. (a) is a quarter of the pellet. (b) is inner core. (c) is middle layer. (d) is outer layer.

Figure 14 shows outer layer is denser than inner core. Middle layer and inner core have lots of pores. However, the size of pores in the inner core is more uniform compared with middle layer. What is more, there are some bright spots in the middle layer and very few in the inner core, which represent iron phase. In figure 14 (c), it can see that iron phase usually exists near the pores where the concentration of reducing gases is higher. Figure 14 (d) shows almost none pores, which means at the later stage of the reduction the dense layer slows down diffusion and reduces the reaction rate.

5. Summary

Reduction of pellets with different densities was studied at different temperatures with H₂-CO gas mixture (flow rate = 0.75 L/min, H₂/CO = 1.5).

Density has an important role in reduction extent when reaction temperature is less or equal to 1073 K. When temperature reaches to 1123 K, density has less influence on reduction extent. Temperature and density have a synergic effect on reduction extent. Lower density pellets have higher reduction extent and reduction rate. The reduction extent is highest for highest porosity pellets. Pellets size may affect the reaction rate as the results of comparing reduction curves of pellets which were 1223 K sintered for 9 hours.

The carbon deposition occurred for high density pellets at lower temperatures, 973 K and 1023 K. This may be due to high concentration of product gas in the pellet and slow diffusion, which stops reaction and increases carbon activity. Carbon deposition affects the reduction rate due to decreasing diffusion rate of reducing gas.

Results from SEM and LOM, show that the reduction process cannot be described by a single rate controlling step. For high density pellets, the size of pores of in the inner core is more uniform compared with middle layer. Even the initial reaction at low temperature seems like diffusion control ($T_S = 1323$ K, $T_R = 973$ K, $F_R = 0.75$ L/min, H₂/CO = 1.5). Reduced layer is denser compared with unreduced layer. Reaction at initial stages goes much faster than later stages.

6. Future work

The phase and chemical composition can be investigated in different layers of the partly reduced pellets to find out reduction steps. For different porosity pellets, this makes the reduction mechanisms more clear, and can be used for further modeling. In addition how pellets size affect the reduction rate and reduction extent can be studied.

7. References

1. A. Pineau, N. Kanari, I. Gaballah, *Kinetics of reduction of iron oxides by H₂ Part I: Low temperature reduction of hematite*. *Thermochimica Acta*. Vol. 447, 2006, pp. 89-100.
2. A. Pineau, N. Kanari, I. Gaballah, *Kinetics of reduction of iron oxides by H₂ Part II. Low temperature reduction of magnetite*. *Thermochimica Acta*.. Vol. 456, 2007, pp.75-88.
3. A. A. EL-Geassy. *Gaseous reduction of Fe₂O₃ compacts at 600 to 1050 °C*. *Journal of Materials Science*. Vol. 21, 1986, pp. 3889-3900.
4. M. Kazemi, Master Degree Project. *Reduction of Hematite Pellets with CO-H₂ Mixtures*, School of Industrial Engineering and Management, Department of Materials Science and Engineering, Royal Institute of Technology. Sweden, 2011.
5. Q. T. Tsay, W. H. Ray and J. Szekely. *The Modeling of Hematite Reduction with Hydrogen Plus Carbon Monoxide Mixtures*. *Journal of AIChE*. Vol. 22, 1976, pp.1064-1072.
6. K. Higuchi, R.H. Heerema, *Influence of sintering conditions on the reduction behavior of pure hematite compacts*. *Minerals Engineering*, Vol. 16, 2003, pp. 463-477.
7. M. Bahgat, M.H. Khedr. *Reduction kinetics, magnetic behavior and morphological changes during reduction of magnetite single crystal*. *Materials Science and Engineering B*, Vol. 138 2007, pp. 251-258.
8. W.K. Jozwiak, E. Kaczmarek, T.P. Maniecki, W. Ignaczak, W. Maniukiewicz, *Reduction behavior of iron oxides in hydrogen and carbon monoxide atmospheres*. *Applied Catalysis A: General*, Vol. 326, 2007, pp. 17–27.