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Investigating the Aluminothermic Process for Producing Ferrotitanium Alloy from Ilmenite Concentrate

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Abstract: The aluminothermic process is used for producing ferrotitanium alloy (FeTi) from an ilmenite concentrate. In this study, based on thermodynamic calculations and experiments, we investigated the effects of adding varying amounts of exothermal agent (NaClO_3), slag-forming agent (CaO), and reducing agent (Al) on the recovery ratio of Ti in the aluminothermic process. The thermodynamic calculations suggested that the exothermal agent plays a crucial role in producing the FeTi alloy from the ilmenite concentrate and the maximum Ti grade in the FeTi alloy was approximately 30 wt %. Experimentally, it was verified that the FeTi alloy obtained under the optimum mixing conditions contained 30.2–30.8 wt % Ti, 1.1–1.3 wt % Si, 9.5–11.2 wt % Al, and 56.9–58.0 wt % Fe, along with trace impurities and small amounts of gases such as oxygen (0.35–0.66 wt %) and nitrogen (0.01–0.02 wt %). At the optimum mixing conditions, the recovery ratio of Ti into the obtained FeTi alloy phase was 60.6–68.9%. These results matched closely with the thermodynamic calculations. Therefore, the thermodynamic calculations performed herein are expected to significantly contribute toward the development of new processes and improvement in conventional processes for producing various ferroalloys including the FeTi alloy through the aluminothermic process.

Keywords: aluminothermic process; recovery; ilmenite; ferrotitanium

1. Introduction

FeTi alloys are widely used in various industries such as steel, automotive, aerospace, and biomechanics. Generally, they are produced by the remelting process using Ti scrap as the raw Ti source [1–9]. However, the increasing price of Ti scrap and the instability in the supply of Ti scrap limit their applications. Furthermore, it is difficult to block oxygen and nitrogen during the remelting process [9]. Therefore, the aluminothermic process, which can produce FeTi alloy from cheap and abundant ilmenite (FeTiO_3) ore instead of Ti scrap [10–17], has attracted significant attention. This process is also industrially useful for producing ferroalloys such as ferrotungsten, ferromolybdenum, and ferrovanadium, which are used to improve the properties of cast iron and steel [18–20].

Generally, the aluminothermic process uses Al as the reducing agent; sodium chlorate (NaClO_3), potassium chlorate (KClO_3), sodium nitrate (NaNO_3), or potassium nitrate (KNO_3) as the exothermal agent; and calcium oxide (CaO) or fluorspar (CaF_2) as the slag-forming agent to produce the FeTi alloy from FeTiO_3 concentrate [2,21,22]. In the process, vigorous heat is generated due to the chemical reaction between the charges, which is used to produce the FeTi alloy by the melting reduction of ilmenite (FeTiO_3); the production efficiency is significantly affected by the mixing ratio of the charges. Currently, a few studies have been conducted to determine the optimum production conditions.

Chumarev et al. evaluated the production efficiency of the FeTi alloy according to the components of ilmenite (FeTiO_3) [2]. Misra et al. evaluated the recovery efficiency of Ti metals and the consumption of the reducing agent, Al, according to the volume of slag used [23]. However, the thermodynamic calculation of optimum mixing conditions according to the amounts of the compounds used has not been investigated in detail.

Therefore, in this study, thermodynamic calculations were performed on the aluminothermic process for producing the FeTi alloy from ilmenite (FeTiO_3). Based on the calculated data, during the production of FeTi alloy from the FeTiO_3 concentrate, the effects of the amounts of exothermal, slag-forming, and reducing agents (i.e., NaClO_3 , CaO , and Al, respectively) on the recovery of Ti were validated experimentally. We believe that the results obtained herein will provide a foundation for improving the conventional process or a developing new process to produce FeTi alloy from an FeTiO_3 concentrate.

2. Thermodynamic Calculation

When the FeTi alloy is produced from the FeTiO_3 concentrate using the aluminothermic process, the heat of the reaction is generated due to the chemical reaction between the charges. Therefore, the maximum temperature of the system in the reactor was obtained by analyzing the heat of reaction according to the mixing ratio of the charge materials. Additionally, the influence of changes in the amount of the reducing agent (Al) and slag-forming agent (CaO) on the composition of FeTi alloy and slag phases under equilibrium conditions was analyzed. These data are crucial for understanding the production process of the FeTi alloy from the FeTiO_3 concentrate and improving the process technology. In this study, the equilibrium composition of the FeTi alloy and slag phases and the maximum temperature of the system were calculated based on the following assumptions:

- (1) The FeTiO_3 concentrate used in the thermodynamic calculation consists of FeTiO_3 only without any impurities.
- (2) The amount of Al required to reduce 100% of the FeTiO_3 is one equivalent amount.

- (3) The recovery ratio of Ti and Fe in the FeTi alloy phase was 60% and 100%, respectively, and the Ti in the slag was present in the form of TiO . This assumption was only utilized for calculating the maximum temperature of the system. Herein, the recovery ratios were selected based on the previously reported results [16,24].
- (4) The mixing ratio of slag-forming agent (CaO) was set to 30 wt % of CaO with a melting temperature of approximately 1730 °C or lower based on the Al_2O_3 – CaO binary slag system. This assumption was only utilized for calculating the maximum temperature of the system.
- (5) The heat losses were 30% of the reaction heat in the system.
- (6) The activity coefficient of all the compounds considered herein was one.

First, with regard to the variation in the amount of Al in the FeTiO_3 , Al, and CaO system, the equilibrium composition was calculated using HSC Chemistry, Version 5.1, a chemical program developed by Outokumpu Research Oy. Table 1 lists the details of the chemical compounds considered in the calculation.

The amount of Al added was changed from one equivalent to one equivalent + 20%. The mass balance and heat balance were calculated from the equilibrium composition. Based on these results, the maximum temperature generated by the charge reaction was calculated. Then, the maximum temperature of the system was calculated with the amount of Al in the FeTiO_3 , Al, and CaO system and the amount of NaClO_3 in the FeTiO_3 , Al, CaO , and NaClO_3 system.

Table 1. Chemical compounds considered for the thermodynamic calculation in the aluminothermic process.

Gas	Chloride	Oxide	Oxide	Metal Phase
Al (g)	AlCl ₃	Al ₂ O ₃	FeTi ₂ O ₅	Al
AlCl (g)	Al ₂ Cl ₆	Al ₂ O ₃ ·TiO ₂	Fe ₂ TiO ₄	Fe
AlCl ₂ (g)	AlClO	CaAl ₂ O ₄	NaFeO ₂	FeTi
Al ₂ O ₃ (g)	AlOCl	CaAl ₁₂ O ₁₉	Na ₈ Fe ₂ O ₇	Fe ₂ Ti
CaAl ₂ Cl ₈ (g)	CaCl ₂	Ca ₂ Al ₂ O ₅	NaO ₂	Na
CaCl (g)	CaOCl ₂	CaFe ₃ O ₅	Na ₂ O	Ti
CaCl ₂ (g)	FeCl ₂	CaFe ₅ O ₇	Na ₂ O ₂	TiAl
CaO (g)	FeCl ₃	CaO	Na ₂ O·Al ₂ O ₃	TiAl ₃
Cl (g)	FeOCl	CaO·Al ₂ O ₃	Na ₂ O·Fe ₂ O ₃	-
Cl ₂ (g)	NaAlCl ₄	CaO·2Al ₂ O ₃	Na ₂ O·TiO ₂	-
Fe (g)	Na ₂ AlCl ₆	CaO·6Al ₂ O ₃	Na ₂ O·2TiO ₂	-
FeAlCl ₆ (g)	Na ₃ AlCl ₆	2CaO·Al ₂ O ₃	Na ₂ O·3TiO ₂	-
FeCl (g)	NaCl	3CaO·Al ₂ O ₃	4Na ₂ O·5TiO ₂	-
FeCl ₂ (g)	NaClO ₂	12CaO·7Al ₂ O ₃	Na ₂ Ti ₆ O ₁₃	-
FeO (g)	NaClO ₃	4CaO·Al ₂ O ₃ ·Fe ₂ O ₃	TiO	-
FeOCl (g)	NaClO ₄	CaO·Fe ₂ O ₃	TiO ₂	-
NaCl (g)	TiCl ₂	2CaO·Fe ₂ O ₃	Ti ₂ O ₃	-
Na ₂ Cl ₂ (g)	TiClO	CaO·TiO ₂	Ti ₃ O ₂	-
NaO (g)	-	3CaO·2TiO ₂	Ti ₄ O ₇	-
Na ₂ O (g)	-	4CaO·3TiO ₂	Ti ₅ O ₉	-
Na ₂ O ₂ (g)	-	Ca ₃ Ti ₂ O ₇	Ti ₆ O ₁₁	-
O ₂ (g)	-	FeAl ₂ O ₄	Ti ₇ O ₁₃	-
Ti (g)	-	FeNaO ₂	Ti ₈ O ₁₅	-
TiCl (g)	-	FeO	Ti ₉ O ₁₇	-
TiCl ₂ (g)	-	Fe ₂ O ₃	Ti ₁₀ O ₁₉	-
TiClO (g)	-	Fe ₃ O ₄	Ti ₂₀ O ₃₉	-
TiCl ₂ O (g)	-	FeO·TiO ₂	-	-
TiO (g)	-	2FeO·TiO ₂	-	-
TiO ₂ (g)	-	FeTiO ₃	-	-

Herein, the amount of NaClO₃, as an exothermal agent, was calculated based on the TiO₂ content contained in the FeTiO₃. Figure 1 shows the change in maximum temperature with the amount of Al in the FeTiO₃, Al, and CaO system, whereas Figure 2 shows the change in maximum reaction temperature with the amount of NaClO₃ in the FeTiO₃, Al, CaO, and NaClO₃ system. Figure 1 shows that the maximum temperature in the FeTiO₃, Al, and CaO system was lower than 1420 °C regardless of the amount of Al when the exothermal agent (NaClO₃) was not added. However, in the FeTiO₃, Al, CaO, and NaClO₃ system, when the amount of Al was one equivalent, as shown in Figure 2, the maximum temperature of the system was higher than 1750 °C for NaClO₃ greater than 20 wt %. In addition, it was confirmed that when the amount of Al added was one equivalent + 10%, the amount of NaClO₃ should be greater than 15 wt % to maintain the reaction temperature of over 1750 °C. Furthermore, the calculations suggest that the maximum temperature of the system decreased with an increase in the amount of Al. The results suggest that NaClO₃ is essential for producing the FeTi alloy from the FeTiO₃ concentrate utilizing the aluminothermic process. Therefore, the maximum temperature of the system calculated at certain conditions, as shown in Figure 2, was higher than the melting temperature of the slag composition of Al₂O₃ 70 wt %–CaO 30 wt % considered in the thermodynamic calculation. The melting temperature of the considered slag was approximately 1730 °C, as shown in the phase diagram of the Al₂O₃–CaO binary slag system [25] (Figure 3).

Figure 1. Maximum temperature of the aluminothermic process calculated according to the variation in the amount of Al.

Figure 2. Maximum temperature of the aluminothermic process calculated according to the variation in the amount of NaClO₃.

Figure 3. Phase diagram of the Al_2O_3 – CaO binary slag system [10].

Next, based on the above-mentioned assumptions, the equilibrium composition was calculated using the chemical program HSC Chemistry, Version 5.1, for varying amounts of Al and CaO in the aluminothermic process wherein FeTiO_3 , Al, CaO, and NaClO_3 were mixed. Table 1 lists the chemical compounds considered herein, and Figure 4 shows the metal grade of the FeTi alloy and the recovery ratio of Ti and Fe into the FeTi alloy phase according to the amount of Al. The amount of NaClO_3 was fixed at 20 wt % based on the weight of TiO_2 in FeTiO_3 , whereas that of CaO was fixed at 7.5 wt % based on the weight of FeTiO_3 . As shown in Figure 4, the Ti grade in the FeTi alloy phase increased with the amount of Al, and the Ti grade in the alloy phase was the highest (at approximately 30%) in the vicinity of one equivalent of Al. However, the calculation results showed that when the amount of Al increased by more than one equivalent, the Ti grade in the alloy phase decreased gradually; this is because Al, which does not participate in the reaction, melts into the FeTi alloy phase. Therefore, the Al content in the FeTi alloy phase increases with an increase in the amount of Al, as shown in Figure 4. Based on the results of the thermodynamic calculation, when an FeTi alloy containing less than 10 wt % of Al is produced using the aluminothermic process, the maximum Ti grade in the FeTi alloy is anticipated to be approximately 30 wt %. However, the recovery ratio of Ti increases with an increase in the amount of Al, and nearly all the Fe is recovered at 10 wt % or more of Al. Figure 5 shows the recovery ratio of Ti and Fe in the FeTi alloy phase and the amount of compound in the slag according to the amount of CaO. Herein, the added amount of NaClO_3 was fixed at 20 wt % based on the weight of TiO_2 in FeTiO_3 , whereas that of Al was fixed at one equivalent. Figure 5 shows that when the amount of CaO is approximately 7.5 wt % compared to the charge amount of FeTiO_3 , the recovery ratio of Ti is the maximum in the FeTi alloy; however, the recovery ratio of Ti decreases as the amount of CaO increases over 7.5 wt %. Furthermore, TiO and $\text{CaO} \cdot \text{TiO}_2$ contents in the slag phase gradually increase when the amount of CaO is over 7.5 wt %. However, Fe does not appear to be significantly influenced by the amount of CaO; therefore, when the FeTi alloy is produced from the FeTiO_3 concentrate using the aluminothermic process, the amount of reducing agent, Al, should be approximately one equivalent and that of the slag-forming agent, CaO, should be approximately 7 wt % of the FeTiO_3 concentrate.

Figure 4. Metal grade in the FeTi alloy calculated according to the amount of Al (inset: recovery ratio of Ti and Fe calculated according to the amount of Al).

Figure 5. Amount of compound in the slag and recovery ratio of Ti and Fe calculated according to the amount of CaO.

3. Experimental Method

The FeTiO₃ concentrate was used as the raw Ti resource for producing the FeTi alloy, which was mined and sorted in a domestic S mine company and had an average particle size of 59 μm (Malvern Instruments, Malvern, UK, Malvern Instruments Mastersizer S3.01). Table 2 lists the chemical analysis values of the FeTiO₃ concentrate used herein. NaClO₃ powder of 98 wt % or more, produced by DUKSAN company in Korea, was utilized as the exothermal agent and was crushed to 3 mm or

less (Malvern Instruments, Malvern, UK, Malvern Instruments Mastersizer S3.01). CaO powder of 96 wt % or more was utilized as the slag-forming agent, which was produced by the Samchun Chemical company in Korea. The Al metal powder, which acts as the reducing agent and heat source, was a recycled Al powder produced by the JMTECHKOREA company in Korea with an Al grade of 95 wt % or more and an average particle size of 1000 μm (Malvern Instruments, Malvern, UK, Malvern Instruments Mastersizer S3.01). Figure 6 shows the x-ray diffraction pattern of the FeTiO_3 concentrate used herein.

Table 2. Chemical analysis values of the FeTiO_3 concentrate utilized in this study (wt %).

Al_2O_3	CaO	MgO	MnO	Na_2O	P_2O_5	FeTiO_3	Fe_2O_3	SiO_2
0.95	0.21	2.14	0.56	0.02	0.04	87.31	4.49	1.03

Figure 6. X-ray diffraction pattern of the FeTiO_3 concentrate utilized in this study.

Figure 7 shows the aluminothermic reactor used herein, which consisted of a steel box with dimensions of 100 cm $\times$ 80 cm $\times$ 30 cm (width $\times$ length $\times$ height) filled with silica sand, and a space of 25 cm $\times$ 25 cm $\times$ 20 cm (width $\times$ length $\times$ height) was created using refractory bricks around the center of the steel box. In addition, a hood was attached to the top of the aluminothermic reactor. The sample was mixed for approximately 30 min using a sample mixer, as shown in Figure 8.

Under appropriate conditions, the experiment was conducted by mixing the FeTiO_3 concentrate with the requisite amounts of recycled Al, CaO, and NaClO_3 , charging them in the aluminothermic reactor, and then igniting them with a magnesium ribbon. Meanwhile, in the preliminary experiment for producing the FeTi alloy under typical conditions without adding NaClO_3 in the induction furnace, the FeTi alloy could not be produced. This is the reason why most of the reducing agent, Al powder, is consumed by reacting with oxygen in air during heating. Furthermore, the results obtained in the preliminary experiment, which investigated the variation in the Ti recovery ratio with the total charge amount in the aluminothermic reactor, suggested that the FeTi alloy had little impact on the Ti recovery at a total charge of 5 kg or more. Therefore, in all experiments, the total charge amount was fixed to approximately 6 kg ($\pm 1.5\%$).

Figure 7. Photo of the aluminothermic reactor used in this study.

Figure 8. Photo of the sample mixer used in this study.

The FeTi alloy and slag recovered from the FeTiO_3 concentrate were analyzed for Fe by a potassium dichromate titration method and for Si by the loss in weight on volatilization with hydrofluoric acid. The concentrations of Al and Ti were determined by inductively coupled plasma (ICP) spectroscopy (JY-38 plus, Horiba Ltd., Kyoto, Japan). The solution for the ICP analysis was prepared by decomposition with concentrated inorganic acids. The nitrogen and oxygen in the FeTi alloy recovered was also

analyzed by ICP spectroscopy. The XRD patterns were obtained using an x-ray diffractometer (Rigaku D-max-2500PC, Rigaku/MS, Inc., Woodlands, TX, USA) with Cu-K α radiation ($\lambda = 0.154$ nm) operated at 40 kV and 30 mA. In addition, the recovery ratio of Ti and Fe recovered in the FeTi alloy phase was calculated as follows:

$$\text{Ti recovery}(\%) = \frac{\text{Ti weight in FeTi alloy (g)}}{\text{Ti weight in slag (g)} + \text{Ti weight in FeTi alloy (g)}} \times 100 \quad (2)$$

$$\text{Fe recovery}(\%) = \frac{\text{Fe weight in FeTi alloy (g)}}{\text{Fe weight in slag (g)} + \text{Fe weight in FeTi alloy (g)}} \times 100 \quad (3)$$

4. Results and Discussion

4.1. Effect of the Exothermal Agent

When the FeTi alloy was produced from the FeTiO₃ concentrate using the aluminothermic process, we investigated the effect of the amount of NaClO₃ on the recovery of Ti and Fe into the FeTi alloy phase by changing the amount of NaClO₃ compared to the weight of TiO₂ in the FeTiO₃ concentrate from 0 to 25 wt %. In this experiment, the slag-forming agent, CaO, was added based on 30 wt % of CaO in the expected slag composition of the Al₂O₃–CaO binary slag system, and one equivalent of Al was added to the charge. Table 3 lists the charge amounts for each experiment, and Figure 9 shows the effects of adding an exothermal agent on the recovery of Ti and Fe in the FeTi alloy phase. This figure shows that the FeTi alloy cannot be produced from the FeTiO₃ concentrate only by the heat generated due to the self-reaction between Al and the charge without the addition of NaClO₃. However, it was confirmed that the recovery of Ti and Fe increased with an increase in the amount of NaClO₃. Specifically, the recovery ratio of Ti was greater than 62%, when 15 wt % or more of NaClO₃ was added, suggesting that the recovery ratio does not change significantly; however, nearly all the Fe was recovered. Accordingly, we concluded that the addition of NaClO₃ is appropriate due to heat loss when there is approximately 20 wt % of the TiO₂ content in the charged FeTiO₃ concentrate.

Table 3. Charge amount for producing the FeTi alloy from the FeTiO₃ concentrate according to the amount of the exothermal agent (NaClO₃).

Sample No.	NaClO ₃ (g)	FeTiO ₃ Concentrate (g)	Recycled Al (g)	CaO (g)
1	-	3770.5	1 equivalent = 1300.0	929.5
2	10 wt % relative to the TiO ₂ component in the charged FeTiO ₃ concentrate = 169.9	3565.8	1 equivalent = 1315.6	948.8
3	15 wt % relative to the TiO ₂ component in the charged FeTiO ₃ concentrate = 248.1	3471.5	1 equivalent = 1322.7	957.6
4	20 wt % relative to the TiO ₂ component in the charged FeTiO ₃ concentrate = 322.3	3382.1	1 equivalent = 1329.5	966.0
5	25 wt % relative to the TiO ₂ component in the charged FeTiO ₃ concentrate = 392.8	3297.2	1 equivalent = 1336	974.0

Figure 9. Recovery ratio of Ti and Fe according to the amount of NaClO₃.

4.2. Effect of the Slag-Forming Agent

Table 4 shows the charge ratio used to investigate the effect of adding CaO on the recovery of Ti and Fe into the FeTi alloy phase. CaO was selected as the slag-forming agent since it has a higher affinity for oxygen than Al and forms a relatively low-temperature complex oxide. Thus, we investigated the recovery ratio of Ti and Fe in the FeTi alloy phase according to the amount of CaO. In this experiment, the amount of NaClO₃ was fixed as 20 wt % of the weight of TiO₂ in the FeTiO₃ concentrate, and one equivalent of Al was added to react with the oxides that could be reduced by Al in the charge. Figure 10 shows the recovery ratio of Ti and Fe in the FeTi alloy phase according to the amount of CaO added during the aluminothermic process. As shown in Figure 10, the recovery ratio of Ti and Fe was relatively constant from 7.2 to 28.6 wt % of the amount of CaO, and then, the ratio decreased at 35.9 wt %. This trend was slightly different from the theoretical calculation result in the previous section (Figure 5), which is possibly attributed to the impurities in the FeTiO₃ concentrate, as shown in Table 2. Accordingly, in the aluminothermic process for producing the FeTi alloy from the FeTiO₃ concentrate, the appropriate amount of CaO to add was approximately 16.6 wt % of the amount of the FeTiO₃ concentrate.

Table 4. Charge amount for investigating the effect of the addition of CaO on the recovery of Ti and Fe in the FeTi alloy phase.

Sample No.	FeTiO ₃ Concentrate (g)	Recycled Al (g)	CaO (g)	NaClO ₃ (g)
1	3844.1	1 equivalent = 1511.1	278.4	366.3
2	3627.3	1 equivalent = 1425.9	601.1	345.7
3	3508.6	1 equivalent = 1379.3	777.8	334.4
4	3382.1	1 equivalent = 1329.5	966.0	322.3
5	3247.0	1 equivalent = 1276.4	1167.1	309.4

Figure 10. Recovery ratio of Ti and Fe according to the addition amount of CaO.

4.3. Effect of the Reducing Agent

We investigated the effect of the amount of recycled Al on the production of the FeTi alloy from the FeTiO_3 concentrate. In this experiment, the amount of NaClO_3 was fixed as 20 wt % compared to the weight of TiO_2 contained in the FeTiO_3 , and the amount of the CaO was fixed at 16.6 wt % compared to the charge amount of the FeTiO_3 concentrate. The amount of recycled Al was changed from 23.8 wt % (one equivalent) to 24.8 wt % (one equivalent + 6%) compared to the total charge amount. This is because the Ti grade in the FeTi alloy phase was the highest at approximately 30% in the vicinity of one equivalent of Al, as obtained via the thermodynamic calculations (Figure 4). Figure 11 presents the experimental results for the amount of Al in the production process of the FeTi alloy from the FeTiO_3 concentrate, which shows that the recovery ratio of Ti increased from 60.6% to 68.9% as the added amount of recycled Al increased. In addition, it was shown that the Ti grade in the FeTi alloy decreased slightly after 24 wt % of the amount of recycled Al. This indicates that the Al grade in the FeTi alloy increased as the added amount of recycled Al increased, which agreed with the above-mentioned thermodynamic calculation (Figure 4). As shown in Table 5, which presents the charge amount, the amount of the FeTi alloy, and chemical composition of the FeTi alloy, the FeTi alloy produced by varying the charge amount contained approximately 30.2–30.8 wt % Ti, 1.1–1.3 wt % Si, 9.5–11.2 wt % Al, 56.9–58.0 wt % Fe, and trace impurities. Utilizing a nitrogen/oxygen analyzer, the FeTi alloy was found to contain 0.35–0.66 wt % oxygen and 0.01–0.02 wt % nitrogen. The oxygen and nitrogen concentrations contained in the FeTi alloy were lower than those contained in the FeTi alloy produced from Ti scrap in a generally known atmosphere [25]. Figure 12 shows an image of the FeTi alloy obtained herein and the XRD pattern. The XRD analysis revealed that the FeTi alloy primarily contained Fe_2Ti , AlFe_3 , and Fe phases. From the above experimental results, the optimum mixing conditions were found to be NaClO_3 at 20 wt % relative to the weight of TiO_2 contained in the FeTiO_3 concentrate; recycled Al powder between 23.8 wt % (one equivalent) and 24.8 wt % (one equivalent + 6%) relative to the total charge amount; and CaO at 16.6 wt % relative to the charge amount of the FeTiO_3 concentrate. It was also confirmed that when the FeTi alloy containing less than 10 wt % of Al was produced from the FeTiO_3 concentrate by the aluminothermic process, the Ti grade in the resulting FeTi alloy was approximately 30 wt %. This agreed well with the results from the thermodynamic calculation.

Figure 11. Effect of the added amount of recycled Al on the recovery of Ti and Fe in the FeTi alloy phase.

Table 5. Chemical composition and amount of FeTi alloy produced by varying the charge.

Sample No.	Composition of FeTi Alloy Phase (wt %)				Charge Amount		Produced Alloy Weight
	Ti	Al	Fe	Si	Recycled Al	FeTiO ₃ Concentrate/ CaO/NaClO ₃	
1	30.2	9.5	58.0	1.1	23.8 wt % relative to total charge amount (1 equivalent + 0% = 1425.9 g)	3627.3 g/601.1 g/345.7 g	1917 g
2	30.8	9.6	57.7	1.3	24.0 wt % relative to total charge amount (1 equivalent + 1.5% = 1447.3 g)		2001 g
3	30.6	10.4	57.6	1.3	24.3 wt % relative to total charge amount (1 equivalent + 3% = 1468.7 g)		2073 g
4	30.5	11.2	56.9	1.2	24.8 wt % relative to total charge amount (1 equivalent + 6% = 1511.5 g)		2191 g

Figure 12. Photo and x-ray diffraction (XRD) pattern of the FeTi alloy produced from this study.

5. Conclusions

Herein, the aluminothermic process for producing the FeTi alloy from an FeTiO₃ concentrate was investigated through thermodynamic calculation and validated experimentally. Through the theoretical thermodynamic calculations, the importance of an exothermal agent, NaClO₃, in the production of FeTi

alloy from an FeTiO₃ concentrate was confirmed, and the optimum mixing conditions according to the amount of the compounds were predicted. From the thermodynamic calculations and experimental results, the optimum mixing conditions were:

- NaClO₃: 20 wt % relative to the weight of TiO₂ contained in the FeTiO₃ concentrate.
- Recycled Al powder: Between 23.8 wt % (one equivalent) and 24.8 wt % (one equivalent + 6%) relative to the total charge amount.
- CaO: 16.6 wt % relative to the charge amount of the FeTiO₃ concentrate.

The FeTi alloy produced in the optimum mixing conditions contained 30.2–30.8 wt % Ti, 1.1–1.3 wt % Si, 9.5–11.2 wt % Al, and 56.9–58.0 wt % Fe. Under the same conditions, the recovery ratio of Ti in the FeTi alloy phase was 60.6–68.9%, which agreed well with the thermodynamic calculations. The thermodynamic prediction performed herein is expected to contribute toward the development of new processes and the improvement of conventional processes for producing various alloys such as ferrotungsten, ferromolybdenum, and ferrovandium including the FeTi alloy through the aluminothermic process. In addition, these results can provide a versatile approach to the scale-up strategy of the industrial aluminothermic process.

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