Mechanism of Change in Chemical Composition of Oxide Inclusions in Fe–Cr Alloys Deoxidized with Mn and Si by Heat Treatment at 1 473 K

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The MnO–SiO2-type inclusions changed into MnO–Cr2O3 type inclusions in an Fe–Cr alloy deoxidised by Mn and Si with a low Si concentration by heat treatment at 1 473 K. At high Si content, the MnO–SiO2-type inclusion remained stable even after heat treatment. The change in the chemical composition of the oxide inclusions by heat treatment depended on the concentrations of Si and Cr in the Fe–Cr alloys. The mechanism of the change in the chemical composition of the oxide inclusions was investigated by using two experimental methods. The solubility of Cr2O3 in MnO–SiO2 was measured from 1473 to 1673 K. The solubility of Cr2O3 decreased with temperature. The other experiment was performed using a diffusion couple method between the Fe–Cr alloy and MnO–SiO2 at 1 473 K to investigate a reaction between them. The formation of MnO–Cr2O3 was observed at the interface. It is found that both the decrease in solubility of Cr2O3 and diffusion of Mn, Cr, and Si at the interface between the Fe–Cr alloy and oxide inclusions are important for controlling the change in the chemical composition of the oxide inclusions in the Fe–Cr alloy by heat treatment at 1 473 K.

KEY WORDS: oxide inclusion; Fe–Cr alloy; heat treatment; composition change; diffusion couple.

1. Introduction

Oxide inclusions in steel play an important role in controlling the metallographic structure by deciding the nucleation sites for solidification and austenite-to-ferrite phase transformation and inducing a pinning effect that inhibits grain boundary migration. Kimura et al.1) showed that the solidification structure of high-purity ferritic stainless steel can be refined by a special oxidation treatment. Fujimura et al.2) showed that the precipitation of Ti nitride on MgO–Al2O3 leads to the formation of an equiaxed solidification structure. It is necessary to control the grain size of steel products; however, oxides precipitated during solidification are coarse and have low number densities. It is therefore difficult to make the grain size finer by using these oxides.

It is known that the oxide composition of stainless steel changes from MnO–Cr2O3 to MnO–SiO2 or SiO2 with an increase in the Si content. Tanahashi et al.3) conducted a thermodynamic analysis and reported that the differences in the equilibrium oxygen activities among these oxides are small; the oxides with low Si content have the lowest oxygen activity, and hence, their chemical compositions change. Further, it is known that heat treatment of stainless steel changes chemical composition in the oxide inclusions. Takahashi et al.4) showed that the oxide composition changed from MnO–SiO2 to MnO–Cr2O3 by heat treatment at 1 373 and 1 573 K. This phenomenon was influenced by the Mn and Si contents; when the Si content exceeded approximately 0.3%, the composition of MnO–SiO2 was not influenced by heat treatment, and it remained unchanged. Takano et al.5) reported that after heat treatment and hot rolling, MnO–SiO2 observed in an as-cast sample disappeared and fine MnO–Cr2O3 appeared. They concluded that the dissolution of MnO–SiO2 and the precipitation of MnO–Cr2O3 had occurred. Further, they showed that the grain size became very fine because of the precipitation of fine MnO–Cr2O3. This is the only study on stainless steel that showed the effect of change in oxide composition to another oxide led to the formation of a fine grain structure. In their study, however, the effect of the hot rolling on the change in the chemical composition of the oxide was not clear. Later, Kimura et al.6) reported the change in the chemical composition of the oxide inclusions of stainless steel without the hot rolling process. Shibata et al.7) also recently investigated the effect of Cr content in the Fe–Cr alloy deoxidized by Mn and Si on the change in the chemical composition of the
oxide inclusions without the hot rolling process by heat treatment at 1 473 K for 60 min. The change in the chemical composition of the oxide inclusions from MnO–SiO₂ to MnO–Cr₂O₃ has been observed above 1 mass% Cr with low Si concentrations by heat treatment.

Hence, the two mechanisms that change the composition of the oxide inclusions of the Fe–Cr alloy in the solid state are described below:

(1) Cr₂O₃ dissolved in MnO–SiO₂ may precipitate MnO–Cr₂O₃ with decreasing temperature owing to the decrease in the solubility of Cr₂O₃ in MnO–SiO₂.

(2) Stable oxide inclusions in Fe–Cr steel alloy at 1 473 K may change from MnO–SiO₂-type inclusions to MnO–Cr₂O₃-type inclusions. A reaction between the oxide inclusions and the alloy may occur by diffusion of the elements.

Therefore, in this study, the mechanism of the change in the chemical composition of the inclusions was investigated by performing two experiments. One was the measurement of the solubility of Cr₂O₃ in the MnO–SiO₂–Cr₂O₃ system. The other was a diffusion couple experiment performed using a metal sample and an oxide sample to clarify the diffusion of Cr, Mn, and Si at the interface between the inclusions and a matrix metal phase; metal samples were used because it is very difficult to measure the change in the chemical composition in the metal phase near the small inclusions. Furthermore, the effect of the holding time for heat treatment at 1 473 K on the change in the chemical composition of the oxides in the Fe–Cr alloy was investigated.

2. Experimental Method

2.1. Effect of the Holding Time for Heat Treatment on the Change in the Chemical Composition of the Oxides in the Fe–Cr Alloy at 1 473 K

Electrolytic iron with chromium was melted by using an arc melting furnace. The premelted iron alloy (approximately 100 g) was melted again in an alumina crucible with Si and Mn at 1 873 K for 15 min under an air atmosphere. After 15 min, the sample in the crucible (inner diameter: 20 mm, height: 57 mm) was quenched with water. The compositions of the alloys were selected from the results of the previous study. After heat treatment, MnO–Cr₂O₃ was stable in sample (A) with low Si content. MnO–SiO₂ was stable in sample (B) with high Si content. The compositions of the alloy are summarized in Table 1. Both surfaces of the disk-shaped sample were mirror polished. Oxide disk, which simulates the deoxidation products, was also made. The chemical composition of the oxides with different chemical compositions was melted in a small platinum crucible at 1 873 K under a controlled oxygen partial pressure, Po₂ = 2 × 10⁻⁶ Pa. The oxygen partial pressure was controlled by using a mixture gas of CO and CO₂. Each sample was then cooled to the desired temperature and maintained for 24 h at 1 473, 1 573, and 1 673 K. The oxygen partial pressure was kept constant by varying the mixture ratio of CO and CO₂ during the heat treatments. Then, the sample along with the platinum crucible was quenched in oil under a controlled atmosphere. The cross section of the sample was observed by using an electron microprobe analyzer (EPMA), and the chemical composition of the observed phase was measured.

2.2. Measurement of Solubility of Cr₂O₃ in MnO–SiO₂–Cr₂O₃

Five samples with different chemical compositions of oxide were investigated to clarify the solubility of Cr₂O₃ in MnO–SiO₂–Cr₂O₃. The chemical composition of the slag is listed in Table 2. The chemical composition was chosen by referring to the phase diagram of MnO–SiO₂–Cr₂O₃. Each composition was close to the liquidus line, which is in equilibrium with the different oxide phases. The mixture of each of the oxides with different chemical compositions was melted in a small platinum crucible at 1 873 K under a controlled oxygen partial pressure, Po₂ = 2 × 10⁻⁶ Pa. The oxygen partial pressure was controlled by using a mixture gas of CO and CO₂. Each sample was then cooled to the desired temperature and maintained for 24 h at 1 473, 1 573, and 1 673 K. The oxygen partial pressure was kept constant by varying the mixture ratio of CO and CO₂ during the heat treatments. Then, the sample along with the platinum crucible was quenched in oil under a controlled atmosphere. The cross section of the sample was observed by using an electron microprobe analyzer (EPMA), and the chemical composition of the observed phase was measured.

2.3. Diffusion Couple Experiment for the Fe–Cr Alloy

Electrolytic iron with chromium, manganese, and silicon was melted in an arc melting furnace. The premelted iron alloy (approximately 100 g) was cut into a disk shape, 7 mm in diameter and 6 mm in height. Two chemical compositions of the alloy were selected from the results of the previous study. After heat treatment, MnO–Cr₂O₃ was stable in sample (A) with low Si content. MnO–SiO₂ was stable in sample (B) with high Si content. The compositions of the alloy are summarized in Table 3. Both surfaces of the disk-shaped sample were mirror polished. Oxide disk, which simulates the deoxidation products, was also made. The chemical composition of the oxides was selected to be 61.7 mol% MnO and 38.3 mol% SiO₂; this composition is close to the eutectic point between MnO and SiO₂ in the phase diagram.

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<table>
<thead>
<tr>
<th>Slag No.</th>
<th>MnO</th>
<th>SiO₂</th>
<th>Cr₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>41.8</td>
<td>54.9</td>
<td>3.3</td>
</tr>
<tr>
<td>B</td>
<td>43.6</td>
<td>50.7</td>
<td>5.7</td>
</tr>
<tr>
<td>C</td>
<td>54.0</td>
<td>43.5</td>
<td>2.5</td>
</tr>
<tr>
<td>D</td>
<td>63.2</td>
<td>34.3</td>
<td>2.5</td>
</tr>
<tr>
<td>E</td>
<td>68.8</td>
<td>29.3</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 3. Chemical compositions of the Fe-Cr alloys used for the diffusion couple experiments.

<table>
<thead>
<tr>
<th></th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>1.4Mn–0.1Si</td>
<td>1.38</td>
<td>0.11</td>
<td>9.71</td>
<td>88.80</td>
</tr>
<tr>
<td>(B)</td>
<td>1.3Mn–0.8Si</td>
<td>1.28</td>
<td>0.84</td>
<td>9.47</td>
<td>88.41</td>
</tr>
</tbody>
</table>

Table 2. Chemical compositions of the oxides used for measurement of the solubility of Cr₂O₃ in MnO–SiO₂.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Fe (%)</th>
<th>Cr (%)</th>
<th>Mn (%)</th>
<th>Si (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Fe–10%Cr Low-Si</td>
<td>89.17</td>
<td>9.63</td>
<td>1.12</td>
<td>0.08</td>
</tr>
<tr>
<td>(ii) Fe–10%Cr High-Si</td>
<td>88.98</td>
<td>9.68</td>
<td>1.04</td>
<td>0.30</td>
</tr>
<tr>
<td>(iii) Fe–5%Cr Low-Si</td>
<td>94.46</td>
<td>4.77</td>
<td>0.75</td>
<td>0.03</td>
</tr>
<tr>
<td>(iv) Fe–5%Cr Mid-Si</td>
<td>94.18</td>
<td>4.66</td>
<td>1.02</td>
<td>0.15</td>
</tr>
<tr>
<td>(v) Fe–5%Cr High-Si</td>
<td>93.19</td>
<td>4.96</td>
<td>1.43</td>
<td>0.43</td>
</tr>
<tr>
<td>(vi) Fe–1%Cr Low-Si</td>
<td>98.48</td>
<td>1.00</td>
<td>0.49</td>
<td>0.03</td>
</tr>
<tr>
<td>(vii) Fe–1%Cr High-Si</td>
<td>97.79</td>
<td>0.99</td>
<td>0.86</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 1. Chemical compositions of Fe–Cr alloys.
diameter and 2 mm in height, and both surfaces of the oxide disk were mirror polished.

Three metal disks and one oxide disk were set as shown in Fig. 1. The whole sample set was placed in a hot deformation simulator and then sandwiched by Si3N4 rods. The hot deformation simulator can load the sample through the Si3N4 rods and heat the sample set by using an induction heating method. An R-type thermocouple was welded on the metal plate, as shown in Fig. 1. The sample set was heated at 1473 K for 120 min under a 100 N compression load under Ar–10 mass% H2 atmosphere. After heat treatment, the sample set was quenched by He gas in a chamber. A vertical cross section of the quenched sample was mirror polished. Then, the morphology and the chemical composition of the oxide at the interface between the oxide phase and the metal phase and the distribution of O, Cr, Si, Mn, and Fe were observed using the EPMA.

3. Experimental Results

3.1. Observation of the Change in the Chemical Composition of the Oxide in the Fe–Cr Alloy

Figure 2 shows an FE-SEM image of an inclusion in the sample, Fe–10% Cr, with low Si content, containing 9.63 mass% Cr, 1.12 mass% Mn, and 0.08 mass% Si before and after heat treatment at 1473 K for 5, 10, and 60 min. A spherical MnO–SiO2-type inclusion was found in an as-cast sample before heat treatment; its typical chemical composition, measured using the EDS, was 56 mol% SiO2–40 mol% MnO–4 mol% Cr2O3. After heat treatment for 5 min, the shape of the inclusions changed to an irregular shape. The content of Cr2O3 in small portions, indicated by 2 and 3 in Fig. 2, increased to 17 mol%. After heat treatment for 10 min, the shape of the inclusions was irregular. The content of Cr2O3 in the inclusions increased to 44 mol%. After heat treatment for 60 min, inclusions with an irregular shape were observed; their chemical composition was 54 mol% MnO–46 mol% Cr2O3. No Si was detected in the inclusions.

Figure 3 shows an FE-SEM image of the inclusion in the sample, Fe–10% Cr with high Si content, containing 9.68 mass% Cr, 1.04 mass% Mn, and 0.30 mass% Si before and after heat treatment at 1473 K for 5, 10, 60 min. The spherical MnO–SiO2-type inclusion was found in an as-cast sample before heat treatment; its typical chemical composition, measured using the EDS, was 48 mol% SiO2–48 mol% MnO–4 mol% Cr2O3. After heat treatment for 5 min, the shape of the inclusions partially changed to an irregular shape. The content of Cr2O3 was increased to 74 mol%. After heat treatment for 10 min, the shape and the chemical composition were not altered. The content of Cr2O3 in the inclusions did not increase. On the other hand, the content of SiO2 increased to 24 mol%. After heat treatment for 60 min, the chemical composition did not change.
the Fe–Cr alloys containing 10, 5, and 1 mass% Cr with different Si content, before and after heat treatment at 1473 K for 5, 10, 60 min, are summarized in Table 4. The MnO–SiO2-type inclusion in alloys with low Si content became more stable with a decrease in the Cr content. The critical Si content, below which the change in the chemical composition of the oxide inclusions occurs, decreases with the Cr content. In the Fe–Cr alloy containing 1 mass% Cr, MnO–Cr2O3-type inclusions were not observed. Therefore, it was concluded that the change in the chemical composition of the oxide inclusions due to heat treatment depends on the concentration of Cr and Si in the Fe–Cr alloy.

3.2. Solubility of Cr2O3 in MnO–SiO2–Cr2O3

The Cr2O3 content in the MnO–SiO2 phase is shown in Fig. 4. The measured value at 1873 K was taken from the literature. Cr2O3 content in the MnO–SiO2 phase decreases with temperature. The solubility of Cr2O3 in the MnO–SiO2 slag also decreases with temperature. This result implies that MnO–Cr2O3 can precipitate from the deoxidation products that formed in the molten alloy.

3.3. Observation at the Interface between the Oxide and Metal Obtained by the Diffusion Couple Experiment

3.3.1. Sample A: 1.4 Mn–0.1Si with 10 mass% Cr–1.5 mass% Mn–0.2 mass% Si Alloy

The cross section of the interface between the slag and the metal sample was observed by SEM, as shown in Fig. 5. At the interface, a precipitated phase, which is indicated by 1 in the figure, was observed along the interface between the slag and the metal. Two kinds of particles were observed in the metal phase, as indicated by 2 and 3. Two phases were observed in the slag phase, as indicated by 4 and 5. The mapping images of O, Fe, Cr, Si, and Mn were obtained by the EPMA, as shown in Fig. 6. The oxygen concentration in the oxide phase near the interface was high, as indicated by 6. In this layer, Cr was also concentrated. In the metal phase, Cr concentration gradually decreased toward the interface. Figure 6 shows the shape of the Cr concentrated layer superimposed with the precipitated phase 1 in Fig. 1. The concentration of Si in the Cr concentrated layer was very low, and Mn concentration was also relatively low in this layer. It is concluded that the MnO–Cr2O3 layer was formed at the interface using the diffusion couple method after heat treatment. High and low concentration regions of Si were observed in the slag layer, as indicated by 8 and 9, respectively. Several metal particles were also observed in the slag layer, as indicated by 7. On the other hand, several oxide inclusions including Mn and Cr were observed in the metal layer, as indicated by 10 and 11, respectively. These oxide inclusions may be formed by oxidation of the metal phase. Further investigation is required to clarify the mechanism of the formation of the oxide inclusions.

The chemical composition of Cr, Si, and Mn in the metal phase near the interface was also measured by using the EPMA. The measured chemical compositions are plotted in Fig. 7. The concentration of Cr and Mn gradually decreased

| Table 4. Summary of the change in the chemical composition of the oxide inclusions of Fe–Cr alloys before and after heat treatment at 1473 K. |
| Sample | Heating time | As cast | 5 min. | 10 min. | 60 min. |
| Fe–10%Cr (0.08 mass%) | Low-Si | | | | |
| Fe–10%Cr (0.30 mass%) | High-Si | | | | |
| Fe–5%Cr (0.15 mass%) | Mid-Si | | | | |
| Fe–5%Cr (0.43 mass%) | High-Si | | | | |
| Fe–1%Cr (0.03 mass%) | Low-Si | | | | |
| Fe–1%Cr (0.36 mass%) | High-Si | | | | |

| Sample | Heating time | As cast | 5 min. | 10 min. | 60 min. |
| Fe–10%Cr (0.08 mass%) | Low-Si | | | | |
| Fe–10%Cr (0.30 mass%) | High-Si | | | | |
| Fe–5%Cr (0.15 mass%) | Mid-Si | | | | |
| Fe–5%Cr (0.43 mass%) | High-Si | | | | |
| Fe–1%Cr (0.03 mass%) | Low-Si | | | | |
| Fe–1%Cr (0.36 mass%) | High-Si | | | | |

○: MnO–SiO2 type
●: MnO–SiO2 type and MnO–Cr2O3 type
●: MnO–Cr2O3 type

Fig. 4. Change in Cr2O3 content in the MnO–SiO2 phase as a function of temperature.

Fig. 5. SEM image of the interface between the metal phase and the oxide phase in sample (A).
toward the interface. The Si content was too low to detect changes in it. This result implies that the MnO–Cr₂O₃ layer was formed due to the diffusion of Cr and Mn from the metal phase to the oxide phase.

3.3.2. Sample B: 1.4 Mn–0.1Si with 9.47 mass% Cr–1.28 mass% Mn–0.84 mass% Si Alloy

The cross section of sample B is shown in Fig. 8. No precipitated layer was observed at the interface between the metal phase and the oxide phase.
slag and the metal phase. The mapping images of O, Fe, Cr, Si, and Mn were also obtained by using the EPMA, as shown in Fig. 9. The chemical composition was also measured, as shown in Fig. 10. Cr was not concentrated at the interface, and the change in Cr concentration in the metal layer near the interface was very small. The oxide phase was also separated into two phases; one phase had high Si content, and the other had low Si concentration. A small amount of Cr was detected in the slag layer.

4. Discussion

The stability of the oxide phase in the Fe–Cr alloy has been previously discussed by us. The equilibrium oxygen activity calculated for each oxidation reaction at 1873 and 1473 K is shown in Figs. 11(a) and 11(b) for steel containing 10 mass% Cr, 1 mass% Mn. In these calculations, to determine the most stable oxide, we determined the equilibrium oxide composition in each steel composition as a function of Si content, considering the equilibrium between oxygen with each element. The oxygen activity in each reaction that formed oxides was calculated, and it was inferred that the most stable oxide was obtained when oxygen activity was the lowest.

\[
\begin{align*}
[Mn] + [O] &= MnO(s) \quad \Delta G^0 = -227,823 + 97.64T \text{ } \text{ (1)} \\
[Mn] + 2[Cr] + 4[O] &= MnO–Cr_2O_3(s) \quad \Delta G^0 = -1,157,748 + 494.44T \text{ } \text{ (2)} \\
[Si] + 2[O] &= SiO_2(s) \quad \Delta G^0 = -576,440 + 218.2T \text{ } \text{ (3)} \\
[Mn] + [Si] + 3[O] &= MnO–SiO_2(s) \quad \Delta G^0 = -832,223 + 318.26T \text{ } \text{ (4)}
\end{align*}
\]

The critical Si content at 1873 K, where the stable oxide changed from MnO–SiO_2 to MnO–Cr_2O_3, was approximately 0.1 mass% for 10 mass% Cr. The critical Si content at 1473 K, where the stable oxide changed from SiO_2 to MnO–Cr_2O_3, was approximately 0.3 mass% for 10 mass% Cr steel. These results match the observation results even though many assumptions that have no thermodynamic significance were made.

In the case of Fe–10 mass% Cr with low Si content, MnO–SiO_2 gradually changed to MnO–Cr_2O_3 at 1473 K with an increase in the heat treatment time. The stable oxide phase can be estimated on the basis of the results shown in Fig. 11 along with the chemical composition of Si in the Fe–10 mass% Cr alloy. However, the time sequence of the change in the oxide could not be explained from the above discussion. After heat treatments, in the Fe–Cr alloy with low Si concentration, the MnO–SiO_2-type inclusions changed to MnO–Cr_2O_3-type inclusions. The solubility of Cr_2O_3 in MnO–SiO_2 decreases with temperature. The change in the solubility of Cr_2O_3 may govern the change in the oxide at the initial period of heat treatment. After heat treatment for 60 min, Si content in the oxide layer was very small. If MnO–Cr_2O_3 precipitated owing to the change in the solubility of Cr_2O_3 in the MnO phase, remnants of Si should have remained in the oxide particle. Therefore, this phenomenon does not fully explain the change in the solubility of Cr_2O_3. From the diffusion couple experiment, the formation of the MnO–Cr_2O_3 layer was observed and diffusion of Cr and Mn from the metal phase to the interface was detected in sample (A). In the case of sample (B), the formation of the reaction layer and concentration of Cr were not observed. From these facts, it is inferred that the change in the chemical composition of the oxide is driven by two mechanisms toward the stable oxide phase estimated from the results shown in Fig.
11; one is the change in the solubility of Cr₂O₃ in the oxide phase, and the other is the diffusion of Cr and Mn from the metal phase to the interface. Although the diffusion of Si from the oxide phase to the metal phase was not detected by EPMA due to the low concentration of Si, Si must have diffused into the metal phase. Clearly, a MnO–Cr₂O₃ layer was formed because of the diffusion of Mn and Cr from the metal phase to the oxide phase. The equations given below are suggested by the reactions that occurred between the inclusions and the metal phase at the interface.

\[
2\text{SiO}_2(s) + 2[\text{Cr}] + [\text{Mn}] = \text{MnO–Cr}_2\text{O}_3(s) + 3[\text{Si}] \quad \text{......... (5)}
\]

\[
4\text{MnO–SiO}_2(s) + 6[\text{Cr}] = \text{MnO–Cr}_2\text{O}_3(s) + 3[\text{Si}] + [\text{Mn}] \quad \text{................................. (6)}
\]

It is concluded that the decrease in the solubility of Cr₂O₃ in MnO–SiO₂ and the reaction at the interface between the oxide inclusions and the metal phase are the most important factors that govern the change in the oxide inclusions in the Fe–Cr alloy at 1473 K. The content of Si is also important to determine the stable oxide phase in this alloy.

The chemistry of the small oxide inclusion in the alloys was completely changed after the heat treatment at 1473 K for 60 minutes. On the other hand, for the diffusion couple experiments the gradient of the concentration of Cr and Mn were detected in the metal phase after the heat treatment for 120 minutes. Then, the further investigation is required to understand relationship between the heat treatment time and interdiffusion phenomena of the alloying elements.

5. Conclusions

We investigated the effect of the holding time for heat treatment and chemical composition on changes in the Fe–Cr alloy. The mechanism of the heat-treatment-induced change in the chemical composition of the oxide inclusions without any deformation of the structure of the Fe–10 mass% Cr alloy containing different concentrations of Si and Mn was elucidated by performing two experiments. The reaction between the oxide inclusions and the metal phase was also investigated using the diffusion couple method to enhance the diffusion of Cr and Mn. The solubility of Cr₂O₃ in MnO–SiO₂ was also measured. The results obtained from the two experiments were compared with regard to the stable oxide phase using available thermodynamic data. The results obtained from this study are summarized as follows:

1) Changes in the morphology and the chemical composition of the inclusions in the Fe–Cr alloy containing 10% Cr after heat treatment were observed as a function of the heat treatment time. The MnO–SiO₂-type inclusions changed into MnO–Cr₂O₃-type inclusions with a low Si content. At high Si content, the MnO–SiO₂-type inclusion was stable after heat treatment.

2) The solubility of Cr₂O₃ was measured from 1473 to 1673 K. The solubility decreased considerably with temperature. The diffusion couple method was successfully used to investigate the reaction between the oxide inclusions and the metal phase. Both the decrease in the solubility of Cr₂O₃ and the reaction at the interface are the main mechanisms that change the chemical composition of the oxides in the Fe–Cr alloys.

There is a lack of thermodynamic data for the Fe–Cr alloy in the solid state at low temperatures; therefore, further investigations are necessary to estimate the critical component of the alloying element and the temperature, which would allow us to control the chemical composition of the inclusions during heat treatments.

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