Thermodynamics of oxygen solutions in the Fe-Co-Cr melts containing silicon, titanium, and aluminum

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Abstract. Effect of Si, Ti, and Al on the oxygen solubility in the Fe-Co-Cr melts at 1873 K was thermodynamically analyzed. At low Si, Ti, and Al contents, the oxygen concentration increases very slightly. At the higher their contents, when the mechanism of interaction of Si, Ti and Al with oxygen is changed, just these elements determine the oxygen solubility in melt and the oxygen concentration decreases significantly.

1. Introduction

The Fe-Co-Cr alloys are widely used in the current technology as magnetically hard materials and for the production of heaters for the treatment of ground formations in the course of hydrocarbon extraction. The great number of Fe-Co-Cr alloys contain Si, Ti and Al. Oxygen is a harmful impurity in these alloys. A presence of oxygen in these alloys causes a degradation of their physicomechanical and service characteristics. The study of physicochemical properties of oxygen solutions in the Fe-Co-Cr alloys containing Si, Ti and Al has not only the theoretical but also essential commercial importance.

2. Thermodynamic consideration

In the Fe-Co-Cr melts, when the chromium content is higher than 2.0-2.5% (depending on the cobalt content), Cr₂O₃ is the product of interaction of chromium with oxygen in melt [1].

\[
\text{Cr}_2\text{O}_3(s) = 2[\text{Cr}] + 3[\text{O}],
\]

For reaction (1), the oxygen concentration being in equilibrium with a certain chromium content in melt can be calculated according to the equation

\[
\lg[\%O]_{Cr} = \frac{1}{3} \left[ \lg K_{Cr} + \lg a_{Cr_2O_3} - 2 \lg[\%Cr] - \left[ 2e_{\text{Cr}}^{0} + 3e_{\text{O}}^{0} \right][\%Cr] - \left[ 3e_{\text{O}}^{0} + 2e_{\text{Cr}}^{0} \right][\%O] - 3f_{\text{O}}^{0}[\%Cr]^2 \right].
\]

As Cr₂O₃ oxide is solid at 1873 K \((T_m = 2603 \text{ K})\), \(a_{Cr_2O_3} = 1\). The \([\%O]\) value in the right side of eq. (2) can be expressed as \(\left( K_{Cr} / [\%Cr]^2 f_{Cr}^{0} f_{O}^{0} \right)^{1/3} \). At \([\%O] \rightarrow 0\), the activity coefficient \(f_{O} \rightarrow 1\).
Due to the smallness of $[\%O]$, one can assume that 
$$ \frac{\left( K_{\text{Cr}}/[\%Cr]\right)^2}{f_{\text{Cr}}^0} \approx \left( \frac{K_{\text{Cr}}}{[\%Cr]} \right)^2 f_{\text{Cr}}. $$
Then eq. (2) becomes

$$ \log[\%O]_{\text{Cr}} = \frac{1}{3} \left( \log K_{\text{Cr}} - 2 \log[\%Cr] - 2\varepsilon_{\text{Cr}} + \varepsilon_{\text{O}} \right) - 3\varepsilon_{\text{O}} \left[ \frac{K_{\text{Cr}}}{[\%Cr]} f_{\text{Cr}} \right]^{1/3} = \frac{1}{3} \left( \log K_{\text{Cr}} - 2 \log[\%Cr] - 2\varepsilon_{\text{Cr}} + \varepsilon_{\text{O}} \right). $$

In the Fe-Co-Cr-R melts, at low contents of deoxidizer $R$, chromium can be the stronger deoxidizer. In this case, eq. (2a) becomes

$$ \log[\%O]_{\text{Cr}+R} = \frac{1}{3} \left( \log K_{\text{Cr}} - 2 \log[\%Cr] - 2\varepsilon_{\text{Cr}} + \varepsilon_{\text{O}} \right) - 3\varepsilon_{\text{O}} \left[ \frac{K_{\text{Cr}}}{[\%Cr]} f_{\text{Cr}} \right]^{1/3} = \frac{1}{3} \left( \log K_{\text{Cr}} - 2 \log[\%Cr] - 2\varepsilon_{\text{Cr}} + \varepsilon_{\text{O}} \right). $$

The interaction of deoxidizer with oxygen at its higher concentrations, when it is already the stronger deoxidizer, can be described as

$$ R_m O_n(s) = m[R] + n[O], \quad K_R = \left( \left[\%R\right] f_R \right)^m \left( \left[\%O\right] f_O \right)^n. $$

The oxygen concentration in equilibrium with a given deoxidizer content can be calculated according to the equation

$$ \log[\%O]_{\text{R}+\text{Cr}} = \frac{1}{n} \left( \log K_R + \log a_{\text{R},\text{O}_n} - m \log[\%R] - m \varepsilon_{\text{R}} + n \varepsilon_{\text{O}} \right) - m \varepsilon_{\text{R}} - m \varepsilon_{\text{O}} \left[ \frac{K_R}{\left[\%R\right] f_R} \right]^{1/n}. $$

The combined solution of (3) and (5) allows one to determine the deoxidizer concentration corresponding to a change in the deoxidation mechanism.

As for the Fe-Co-Cr melts, two compositions of alloy base are selected among a great variety of them which were the most frequently used. They are Fe-10% Co-10% Cr (alloy I) and Fe-20% Co-25% Cr (alloy II). The equilibrium constants of deoxidation of the iron-cobalt alloys containing 10 and 20% Co with Cr, Si, Ti and Al and also the interaction parameters characterizing these melts are given in Table 1.

In the Fe-10% Co and Fe-20% Co melts at 1873 K, the oxygen solubility is 0.21 и 0.19% respectively [12]. The equilibrium oxygen concentrations calculated by eq. (2a) for alloys I and II are the following:

- **alloy I**
  $$ \log[\%O]_{\text{Cr}} = -1.281 - \frac{2}{3} \log[\%Cr] + 0.0536 \log[\%Cr] + \frac{1.450 \cdot 10^{-2}}{[\%Cr]^2} - 5.259 \cdot 10^{-4} \log[\%Cr]^2 = -1.461; $$
  $$ [O] = 3.462 \cdot 10^{-2\%}; $$
- **alloy II**
  $$ \log[\%O]_{\text{Cr}} = -1.304 - \frac{2}{3} \log[\%Cr] + 0.0553 \log[\%Cr] + \frac{1.318 \cdot 10^{-2}}{[\%Cr]^2} - 4.745 \cdot 10^{-4} \log[\%Cr]^2 = -1.147; $$
  $$ [O] = 7.123 \cdot 10^{-2\%}. $$

In the case of deoxidation of alloys I and II with silicon at its low contents, when chromium is the stronger deoxidizer, the oxygen concentration being in equilibrium with the chromium and silicon contents can be calculated by eq. (3)

- **alloy I**
  $$ \log[\%O]_{\text{Cr}+\text{Si}} = -1.461 + 0.080[\%Si]; $$
- **alloy II**
  $$ \log[\%O]_{\text{Cr}+\text{Si}} = -1.147 + 0.092[\%Si]. $$
At the higher silicon contents in melt, the oxygen concentration being in equilibrium with silicon and chromium can be calculated by eq. (5). The SiO$_2$ oxide at 1873 K is solid ($T_m = 1999$ K), therefore $a_{\text{SiO}_2} = 1$. Taking into account the equilibrium constants of deoxidation with silicon and the interaction parameters (Table 1), eq. (5) becomes for alloys I and II respectively

$$\lg\left[\frac{\%O}{\text{Si}+\text{Cr}}\right] = -1.911 - \frac{1}{2} \lg[\%\text{Si}] + 0.030[\%\text{Si}] + 9.152 \times 10^{-4} \left[\frac{\%\text{Si}}{\%\text{Si}}\right]^{1/2};$$

$$\lg\left[\frac{\%O}{\text{Si}+\text{Cr}}\right] = -1.411 - \frac{1}{2} \lg[\%\text{Si}] + 0.045[\%\text{Si}] + 7.419 \times 10^{-4} \left[\frac{\%\text{Si}}{\%\text{Si}}\right]^{1/2}.$$ 

Solving (3) and (5) simultaneously, one can determine the silicon content $[\%\text{Si}]^*$ when a change in the mechanism of deoxidation occurs, namely: for alloy I, $[\text{Si}]^* = 0.126\%$; for alloy II, $[\text{Si}]^* = 0.297\%$.

The equilibrium oxygen concentrations in alloys I and II at 1873 K which were calculated by (3) and (5) are shown in figure 1 as compared to the data on the oxygen solubility in the Fe-Co [12] and Fe-Co-Si [2] melts. The oxygen solubilities in the Fe-Co and Fe-Co-Cr melts are shown by dotted lines. The oxygen concentration depending on the silicon content in the Fe-10% Co and Fe-20% Co melts at 1873 K can be described by the following equations [2]

$$\lg\left[\frac{\%O}{\text{Fe-10\% Co}}\right] = -2.391 - \frac{1}{2} \lg[\%\text{Si}] + 0.030[\%\text{Si}] + 9.152 \times 10^{-4} \left[\frac{\%\text{Si}}{\%\text{Si}}\right]^{1/2};$$

$$\lg\left[\frac{\%O}{\text{Fe-20\% Co}}\right] = -2.471 - \frac{1}{2} \lg[\%\text{Si}] + 0.045[\%\text{Si}] + 7.419 \times 10^{-4} \left[\frac{\%\text{Si}}{\%\text{Si}}\right]^{1/2}.$$ 

Table 1. Equilibrium constants of deoxidation of Fe-10% Co and Fe-20% Co melts and interaction parameters at 1873 K

| Parameter | Fe | Fe-10%Co | Fe-20%Co | Co | Parameter | Fe | Fe-10%Co | Fe-20%Co | Co |
|-----------|----|----------|----------|----|-----------|----|----------|----------|----|
| $\lg K_{\text{Cr}}$ (Cr$_2$O$_3$) | -3.91 [1] | -3.84 | -3.91 | -7.03 [1] | $\varepsilon^\text{Si}_O$ | -0.066 [5] | -0.079 | -0.092 | -0.206 [7] |
| $\lg K_{\text{Si}}$ (SiO$_2$) | -4.64 [2] | -4.78 | -4.95 | -7.20 [2] | $\varepsilon^\text{O}_{\text{Si}}$ | -0.119 [4] | -0.141 | -0.164 | -0.365 [7] |
| $\lg K_{\text{Ti(I)}}$ (TiO$_2$) | -6.13 [3] | -6.13 | -6.15 | -7.63 [3] | $\varepsilon^\text{Ti}_{\text{Fe}}$ | 0.049 [9] | 0.0504 | 0.0518 | 0.064 [3] |
| $\lg K_{\text{Ti(II)}}$ (Ti$_3$O$_5$) | -16.79 [3] | -16.71 | -16.69 | -20.07 [3] | $\varepsilon^\text{Cr}_{\text{Fe}}$ | 0.026 [10] | 0.0275 | 0.0295 | 0.047 [8] |
| $\lg K_{\text{Ti(III)}}$ (Ti$_2$O$_3$) | -10.22 [3] | -10.14 | -10.10 | -12.01 [3] | $\varepsilon^\text{Cr}_{\text{Fe}}$ | 0.024 [10] | 0.0256 | 0.0275 | 0.044 [8] |
| $\lg K_{\text{Al}}$ (Al$_2$O$_3$) | -13.81 [4] | -13.86 | -13.89 | -15.50 [4] | $\varepsilon^\text{Ti}_{\text{O}}$ | -0.34 [9] | -0.355 | -0.370 | -0.505 [3] |
| $\varepsilon^\text{O}_{\text{Ti}}$ | -0.17 [5] | -0.155 | -0.139 | 0 [6] | $\varepsilon^\text{Ti}_{\text{Fe}}$ | -1.03 [9] | -1.071 | -1.117 | -1.52 [3] |
| $\varepsilon^\text{Cr}_{\text{Fe}}$ | 0 [5] | 0 | 0 | 0 [7] | $\varepsilon^\text{Al}_{\text{Al}}$ | 0.043 [5] | 0.046 | 0.049 | 0.076 [7] |
| $\varepsilon^\text{Cr}_{\text{O}}$ | -0.052 [5] | -0.054 | -0.055 | -0.07 [6] | $\varepsilon^\text{Al}_{\text{Cr}}$ | 0.0145 [11] | 0.0169 | 0.0193 | 0.0408 [8] |
| $\varepsilon^\text{Si}_{\text{Fe}}$ | -0.178 [5] | -0.184 | -0.189 | -0.24 [6] | $\varepsilon^\text{Al}_{\text{Al}}$ | 0.0096 [11] | 0.0108 | 0.0121 | 0.0233 [8] |
| $\varepsilon^\text{O}_{\text{Si}}$ | 0.103 [5] | 0.098 | 0.093 | 0.05 [6] | $\varepsilon^\text{Al}_{\text{Cr}}$ | -1.17 [5] | -1.214 | -1.259 | -1.65 [7] |
| $\varepsilon^\text{Cr}_{\text{Fe}}$ | -3·10$^{-4}$ [5] | 0.0008 | 0.0019 | 0.0115 [8] | $\nu^\text{Cr}_{\text{O}}$ | 5.8·10$^{-4}$ [5] | 5.3·10$^{-4}$ | 4.7·10$^{-4}$ | 0 [6] |

$\nu^\text{Cr}_{\text{O}}$
As is seen in figure 1a, at low contents, silicon does not virtually affect the oxygen concentration in the Fe-Co-Cr melts. The further increase in the silicon content causes a decrease in the oxygen concentration.

Upon deoxidation of alloys I and II with titanium at low its contents, when chromium is the stronger deoxidizer, the oxygen concentration being in equilibrium with certain contents of chromium and titanium can be estimated by eq. (3). Taking into account the interaction parameters (Table 1), eq. (3) becomes

\[
\begin{align*}
\text{alloy I} & \quad \log_{10} \left( \frac{\%O}{\%Ti} \right)_{Cr+Ti} = -1.461 + 0.337 \%Ti; \\
\text{alloy II} & \quad \log_{10} \left( \frac{\%O}{\%Ti} \right)_{Cr+Ti} = -1.147 + 0.351 \%Ti.
\end{align*}
\]

Upon deoxidation of Fe-Co-Cr with titanium depending on the titanium content, oxides TiO₂, Ti₃O₅ and Ti₂O₃ can be the reaction products [13]. At the higher titanium content in melt when it is already the stronger deoxidizer depending on the titanium concentration and type of deoxidation product, the oxygen concentration in equilibrium with certain contents of titanium and chromium can be calculated for TiO₂, Ti₃O₅ and Ti₂O₃ by the following equations, respectively:

\[
\begin{align*}
\log_{10} \left( \frac{\%O}{\%Ti} \right)_{Ti+Cr} & = \frac{1}{2} \log_{10} K_{Ti(0)} + \frac{1}{2} \sigma_{TiO₂} - \frac{1}{2} \log_{10} \left( \frac{\%Ti}{\%O} \right) - \left( \frac{1}{2} e^{Cr}_T + e^{Cr}_O \right) [\%Cr] - \left( \frac{1}{2} e^{O}_T + e^{O}_O \right),
\end{align*}
\]

\[
\begin{align*}
&= \left( \frac{1}{2} e^{Cr}_T + e^{Cr}_O \right) [\%Cr] - \left( \frac{1}{2} e^{O}_T + e^{O}_O \right) \left( \frac{K_{Ti(0)} [\%Ti]}{\%O} \right)^{1/2} - e^{O}_O \%[Cr]^2. \\
&= \left( \frac{1}{2} e^{Cr}_T + e^{Cr}_O \right) [\%Cr] - \left( \frac{1}{2} e^{O}_T + e^{O}_O \right) \left( \frac{K_{Ti(0)} [\%Ti]}{\%O} \right)^{1/2} - e^{O}_O \%[Cr]^2. \\
&= \left( \frac{1}{5} e^{Cr}_T + e^{Cr}_O \right) [\%Cr] - \left( \frac{3}{5} e^{O}_T + e^{O}_O \right) \left( \frac{K_{Ti(0)} [\%Ti]}{\%O} \right)^{1/5} - e^{O}_O \%[Cr]^2. \\
&= \left( \frac{1}{3} e^{Cr}_T + e^{Cr}_O \right) [\%Cr] - \left( \frac{2}{3} e^{O}_T + e^{O}_O \right) \left( \frac{K_{Ti(0)} [\%Ti]}{\%O} \right)^{1/3} - e^{O}_O \%[Cr]^2.
\end{align*}
\]

Figure 1. Oxygen concentration depending on the contents of (a) silicon, (b) titanium, and (c) aluminum in the melts (1) Fe-10% Co-Si, (2) Fe-20% Co-Si, (3) Fe-10% Co-10% Cr-Si, (4) Fe-20% Co-25%Cr-Si, (5) Fe-10% Co-Ti, (6) Fe-20% Co-Ti, (7) Fe-10% Co-10% Cr-Ti, (8) Fe-20% Co-25% Cr-Ti, (9) Fe-10% Co-Al, (10) Fe-20% Co-Al, (11) Fe-10% Co-10% Cr-Al and (12) Fe-20% Co-25% Cr-Al at 1873 K.
\[
-\left[\frac{2}{3}c_{\text{Cr}} + c_{\text{O}}\right]^{3/2} - \left[\frac{2}{3}c_{\text{O}} + c_{\text{Cr}}\right]^{3/2} \left(\frac{K_{\text{TiO}_2}}{f_{\text{TiO}_2}^2}\right)^{1/3} - c_{\text{Cr}}^{3/2} = 0.
\]  

(8)

Oxides TiO\(_2\) (\(T_m = 2185 \text{ K}\)), Ti\(_3\)O\(_5\) (\(T_m = 2050 \text{ K}\)), Ti\(_2\)O\(_3\) (\(T_m = 2110 \text{ K}\)) at 1873 K are solid, therefore \(a_{\text{TiO}_2} = 1\), \(a_{\text{Ti}_3\text{O}_5} = 1\), \(a_{\text{Ti}_2\text{O}_3} = 1\). Taking into account the equilibrium constants of deoxidation with titanium and the interaction parameters (Table 1), eqs. (6)-(8) for the TiO\(_2\), Ti\(_3\)O\(_5\) and Ti\(_2\)O\(_3\) formation become, respectively:

\[
\text{alloy I:} \quad \lg[\%\text{O}]_{\text{Ti}_3\text{O}_5} = -2.707 - \frac{1}{2} \lg[\%\text{Ti}] + 0.330[\%\text{Ti}] + \frac{5.979 \times 10^{-4}}{[\%\text{Ti}]^{3/2}};
\]

(6a)

\[
\text{alloy II:} \quad \lg[\%\text{O}]_{\text{Ti}_3\text{O}_5} = -2.330 - \frac{1}{2} \lg[\%\text{Ti}] + 0.345[\%\text{Ti}] + \frac{5.889 \times 10^{-4}}{[\%\text{Ti}]^{3/2}}.
\]

(6b)

\[
\text{alloy I:} \quad \lg[\%\text{O}]_{\text{Ti}_2\text{O}_3} = -3.012 - \frac{3}{2} \lg[\%\text{Ti}] + 0.325[\%\text{Ti}] + \frac{3.630 \times 10^{-4}}{[\%\text{Ti}]^{3/2}};
\]

(7a)

\[
\text{alloy II:} \quad \lg[\%\text{O}]_{\text{Ti}_2\text{O}_3} = -2.663 - \frac{3}{5} \lg[\%\text{Ti}] + 0.339[\%\text{Ti}] + \frac{3.718 \times 10^{-4}}{[\%\text{Ti}]^{3/2}}.
\]

(7b)

\[
\text{alloy I:} \quad \lg[\%\text{O}]_{\text{Ti}_2\text{O}_3} = -3.067 - \frac{2}{3} \lg[\%\text{Ti}] + 0.321[\%\text{Ti}] + \frac{3.620 \times 10^{-4}}{[\%\text{Ti}]^{3/2}};
\]

(8a)

\[
\text{alloy II:} \quad \lg[\%\text{O}]_{\text{Ti}_2\text{O}_3} = -2.737 - \frac{2}{3} \lg[\%\text{Ti}] + 0.336[\%\text{Ti}] + \frac{3.805 \times 10^{-4}}{[\%\text{Ti}]^{3/2}}.
\]

(8b)

Solving eqs. (6a, b) and (7a, b) simultaneously, one can determine the TiO\(_2\)↔Ti\(_3\)O\(_5\) equilibrium point; solving eqs. (7a, b) and (8a, b), it is possible to find that of Ti\(_3\)O\(_5\)↔Ti\(_2\)O\(_3\). The titanium contents corresponding to the equilibrium points ([Ti\(^\circ\)]) are given below.

| Alloy | I                  | II                  |
|-------|--------------------|---------------------|
| [Ti\(^\circ\)], % (TiO\(_2\)↔Ti\(_3\)O\(_5\)) | 8.907 \times 10^{-4} | 4.691 \times 10^{-4} |
| [Ti\(^\circ\)], % (Ti\(_3\)O\(_5\)↔Ti\(_2\)O\(_3\)) | 0.147              | 0.077               |

Solving eq. (3) simultaneously and successively with eqs. (6a, b)-(8a, b), one can determine the titanium content ([Ti\(^\ast\)]) corresponding to a change in the deoxidation mechanism:

| Alloy | I                  | II                  |
|-------|--------------------|---------------------|
| [Ti\(^\ast\)], % (Cr\(_2\)O\(_3\)↔TiO\(_2\)) | 3.224 \times 10^{-3} | 4.305 \times 10^{-3} |
| [Ti\(^\ast\)], % (Cr\(_2\)O\(_3\)↔Ti\(_3\)O\(_5\)) | 2.602 \times 10^{-3} | 2.975 \times 10^{-3} |
| [Ti\(^\ast\)], % (Cr\(_2\)O\(_3\)↔Ti\(_2\)O\(_3\)) | 3.895 \times 10^{-3} | 4.122 \times 10^{-3} |

Since these contents are in the concentration range where Ti\(_3\)O\(_5\) is the deoxidation product, one can conclude that a change in the deoxidation mechanism occurs at 2.602 \times 10^{-3}% Ti for alloy I and at 2.975 \times 10^{-3}% Ti for alloy II. The equilibrium oxygen contents in alloys I and II at 1873 K which were estimated by eqs. (6a, b)-(8a, b) are given in figure 1b as compared to the data on the oxygen solubility in the Fe-Co [12] and Fe-Co-Ti [3] melts. The oxygen concentration depending on the titanium content at 1873 K for the Fe-10% Co and Fe-20% Co alloys can be described respectively for TiO\(_2\) (eqs. 9a, b), Ti\(_3\)O\(_5\) (eqs. 10a, b) and Ti\(_2\)O\(_3\) (eqs. 11a, b) as the products of deoxidation by the following equations [3]:
\[
\begin{align*}
\lg([\%O]_{Fe-10\% Co}) &= -3.062 - \frac{1}{2} \lg([\%Ti]) + 0.330[\%Ti] + \frac{5.979 \times 10^{-4}}{[\%Ti]^{0.5}}; \\
\lg([\%O]_{Fe-20\% Co}) &= -3.074 - \frac{1}{2} \lg([\%Ti]) + 0.345[\%Ti] + \frac{5.889 \times 10^{-4}}{[\%Ti]^{0.5}}; \\
\lg([\%O]_{Fe-10\% Co}) &= -3.342 - \frac{3}{5} \lg([\%Ti]) + 0.325[\%Ti] + \frac{3.630 \times 10^{-4}}{[\%Ti]^{0.5}}; \\
\lg([\%O]_{Fe-20\% Co}) &= -3.338 - \frac{3}{5} \lg([\%Ti]) + 0.339[\%Ti] + \frac{3.718 \times 10^{-4}}{[\%Ti]^{0.5}}; \\
\lg([\%O]_{Fe-10\% Co}) &= -3.380 - \frac{2}{3} \lg([\%Ti]) + 0.321[\%Ti] + \frac{3.620 \times 10^{-4}}{[\%Ti]^{2/3}}; \\
\lg([\%O]_{Fe-20\% Co}) &= -3.366 - \frac{2}{3} \lg([\%Ti]) + 0.336[\%Ti] + \frac{3.805 \times 10^{-4}}{[\%Ti]^{2/3}}.
\end{align*}
\] (9a) (9b) (10a) (10b) (11a) (11b)

As is seen in figure 1b, at low titanium contents, the oxygen concentration in melt increases very slightly. The further rise in the titanium content results in the substantial decrease in the oxygen concentration.

During the deoxidation of alloys I and II with aluminum at its low contents, when chromium is the stronger deoxidizer, the oxygen concentration in equilibrium with chromium and aluminum can be calculated by eq. (3):

\[
\begin{align*}
\text{alloy I} & \quad \lg([\%O]_{Cr+Al}) = -1.461 + 1.203[\%Al]; \\
\text{alloy II} & \quad \lg([\%O]_{Cr+Al}) = -1.147 + 1.246[\%Al].
\end{align*}
\]

At the higher aluminum contents in melt, when it is the stronger deoxidizer, depending on the aluminum concentration, the oxygen concentration being in equilibrium with the given aluminum and chromium contents, can be calculated by eq. (5). Oxide Al\textsubscript{2}O\textsubscript{3} is solid at 1873 K (\(T_m = 2327\) K), \(a_{Al_{2}O_{3}} = 1\). Taking into account the equilibrium constant of deoxidation with aluminum and the interaction parameters (Table 1), eq. (5) takes form for alloys I and II, respectively:

\[
\begin{align*}
\lg([\%O]_{Al+Cr}) &= -4.207 - \frac{2}{3} \lg([\%Al]) + 1.183[\%Al] + \frac{3.666 \times 10^{-5}}{[\%Al]^{2/3}}; \\
\lg([\%O]_{Al+Cr}) &= -3.745 - \frac{2}{3} \lg([\%Al]) + 1.226[\%Al] + \frac{3.656 \times 10^{-5}}{[\%Al]^{2/3}}.
\end{align*}
\]

Solving eqs. (3) and (5) simultaneously, one can determine the aluminum content \([\%Al]\) when the deoxidation mechanism changes. For alloy I, \([\%Al] = 0.759 \times 10^{-4}\); for alloy II, \([\%Al] = 1.270 \times 10^{-4}\). The equilibrium oxygen concentrations calculated by eqs. (3) and (5) for alloys I and II at 1873 K are given in figure 1c in comparison with the data on the oxygen solubility in the Fe-Co [12] and Fe-Co-Al [4] melts. The oxygen concentration depending on the aluminum content for the Fe-10\% Co and Fe-20\% Co alloys at 1873 K can be written by the following equations [4]:

\[
\begin{align*}
\lg([\%O]_{Fe-10\% Co}) &= -4.619 - \frac{2}{3} \lg([\%Al]) + 1.183[\%Al] + \frac{3.666 \times 10^{-5}}{[\%Al]^{2/3}}; \\
\lg([\%O]_{Fe-20\% Co}) &= -4.630 - \frac{2}{3} \lg([\%Al]) + 1.226[\%Al] + \frac{3.656 \times 10^{-5}}{[\%Al]^{2/3}}.
\end{align*}
\]
As is seen in figure 1c, aluminum at low its contents does not virtually affect the oxygen concentration in melt. The further increase in the aluminum content causes a substantial decrease in the oxygen concentration.

3. Conclusion
Based on the results obtained, one can conclude that the use of silicon, titanium, and aluminum as deoxidizers for the Fe-10% Co-10% Cr and Fe-20% Co-25% Cr alloys results in the final products with very low oxygen concentrations.

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