Direct oxygen removal technique for recycling titanium using molten MgCl₂ salt

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Deoxidation of Ti, or direct removal of O dissolved in metallic Ti, is known to be extremely difficult when Mg is used as the deoxidizing agent. This difficulty arises because the chemical potential of O₂, \( \mu_{O_2} \), under Mg/MgO equilibrium is high (approximately \( 10^{-41} \) atm at 1200 K) and is equivalent to that of Ti containing \( \approx 2 \) mass% O at 1200 K. Therefore, when deoxidizing Ti to the commercial level of high-grade pure Ti (below 0.05 mass% O) using an Mg reductant at 1200 K, the activity of the reaction product MgO (aq) must be decreased to below \( \approx 0.025 \), which is difficult in practice. In this study, the removal of O in Ti in molten MgCl₂ salt using an electrochemical technique was examined at \( \approx 1173 \) K with the objective of obtaining Ti containing less than 0.05 mass% O. Ti samples and graphite electrodes immersed in molten MgCl₂ served as the cathode and anode, respectively. A constant voltage was applied between the electrodes using an external DC source. Molten MgCl₂ was employed to produce the deoxidizing agent Mg and to facilitate deoxidation of Ti by decreasing the activity of the reaction product MgO. By applying a voltage of approximately 3.1 V between the electrodes, the chemical potential of Mg in the molten MgCl₂ was increased at the surface of the Ti cathode, and the Ti samples were deoxidized. The resulting O species, mainly formed O²⁻ dissolved in the molten MgCl₂, was removed from the molten salt by reacting with the C anode to form CO (or CO₂) gas. Ti wires containing 0.12 mass% O were deoxidized to less than 0.02 mass% O. In some cases, the O concentration in the Ti samples was reduced to the level of 0.01 mass%, which cannot be accomplished using the conventional Kroll process. The possible application of this deoxidation technique to practical industrial recycling processes is discussed.

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Introduction

In recent years, the recycling of Ti and Ti alloys has become an important issue.\textsuperscript{1,2} The demand for Ti and Ti alloys in the aerospace industry is increasing, and large amounts of Ti scraps are generated from the fabrication of Ti and Ti alloy products. Fig. 1 shows the material flow of Ti in the US.\textsuperscript{1} The volume of scrap generated is greater than the volume of fabricated Ti products.

Commercial Ti and its alloys contain oxygen at approximately 0.1 mass% (1000 mass ppm) as a major impurity. Oxygen contamination of the product must be avoided, because the presence of O deteriorates the mechanical properties of the metals. Table 1 shows the ASTM grades and acceptable impurity concentrations of Ti and its alloys.\textsuperscript{3} In producing commercially pure Ti of ASTM Gr. 1, low-O-containing Ti feed such as high-purity Ti sponge (0.03–0.1 mass% O) produced by the Kroll process\textsuperscript{4} is used. Using large amounts of scrap metal to produce low-O Ti is hindered by the high O level in Ti scrap, which typically exceeds 0.1 mass%. Titanium and its alloys containing more than 0.4 mass% O cannot be recycled into titanium alloys, and these metals are mainly used in cascade recycling as additive elements for steel, aluminum, \textit{etc}.

O removal directly from Ti and its alloys to levels below 0.1 mass% (1000 mass ppm) is very difficult because O dissolves in Ti to form an interstitial solid solution, and because Ti has a strong affinity with O.\textsuperscript{5,6} Table 2 lists some effective methods for direct removal of O from Ti and from TiAl.\textsuperscript{5,6–48} For example, the deoxidation of solid Ti by reaction with chemically active Ca dissolved in CaCl\textsubscript{2} in the temperature range of 1273 to 1473 K has been examined. Okabe \textit{et al.} successfully produced Ti containing less than 50 ppm by mass of O with a high residual resistivity ratio (RRR > 120).\textsuperscript{18,19} Ca metal is one of the most effective deoxidation agents because it has an extremely strong affinity for O and because it

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Estimated material flow of titanium scrap in the U.S. in 2004.\textsuperscript{1} Units in the figure are 10\textsuperscript{3} ton. Values are rounded to the nearest thousand metric tons of contained titanium.}
\end{figure}
has very low solubility in solid Ti. In the Ca-halide flux deoxidation process shown in Table 2, the CaCl$_2$ flux contains the deoxidation agent Ca and facilitates the reaction by diluting the reaction product CaO, thus decreasing the activity of the by-product. However, the purity of flux and the initial O content of the Ti are subject to limits, since the ultimate limit of deoxidation depends on the amounts of both O present as an impurity in the CaCl$_2$ flux and CaO produced during deoxidation.

An effective technique for the preparation of O-free Ti by electrochemical deoxidation using CaCl$_2$ molten salt has been developed.$^{21}$ Removal of O$^{2-}$ (present as CaO in the flux) and production of Ca deoxidant using electro-chemical techniques improved the deoxidation limit of the Ca-halide flux deoxidation process. Under certain conditions, Ti with 0.001 mass% (10 mass ppm) O has been successfully produced by the electrochemical deoxidation technique.

Hashimoto et al. proposed a method for the deoxidation of Ti during electro-winning using molten fluoride salt baths,$^{45-47}$ but contamination of Ti by O or C is unavoidable using this method. In 2001, Chen et al. developed a novel process, called the FFC process, for producing Ti directly from TiO$_2$ immersed in CaCl$_2$ molten salt using electrochemical methods, and they succeeded in obtaining low-O Ti using this process.$^{26-28}$ Ono and Suzuki developed a new Ti reduction process that utilizes electrochemically produced Ca reductant in molten CaCl$_2$ salt.$^{32}$ To obtain low-O Ti, a highly reducing atmosphere is required. For this reason, molten CaCl$_2$ with high metallic Ca activity is employed as the reaction medium. Other recent developments in deoxidation techniques for Ti and its alloys are also listed in Table 2.

Deoxidation of Ti using Mg as the deoxidizing agent is believed to be almost impossible. This is because the deoxidation limit of a Ti–O solid solution by Mg under MgO saturation is about 2 mass% (20 000 mass ppm) at 1200 K; reducing the deoxidation limit to the level of 100 mass ppm is difficult from a practical perspective. However, if deoxidation of Ti using a MgCl$_2$ medium becomes feasible, the reduction and electrolysis facilities of the conventional Kroll process$^4$ could be utilized. Therefore, developing an effective deoxidation process for Ti and its alloys using molten MgCl$_2$ is expected to significantly enhance the recovery rate for Ti scraps and the production of low-O-containing Ti.

### Table 1 Grades and impurity concentrations of pure titanium and titanium alloys

| Specification | C  | H  | O  | N  | Fe | Al  | V  |
|---------------|----|----|----|----|----|-----|----|
| Pure Ti       | ≤0.08 | ≤0.015 | ≤0.18 | ≤0.03 | ≤0.2 | — | — |
| ASTM Gr. 1    | ≤0.08 | ≤0.015 | ≤0.25 | ≤0.03 | ≤0.3 | — | — |
| ASTM Gr. 2    | ≤0.08 | ≤0.015 | ≤0.35 | ≤0.05 | ≤0.3 | — | — |
| ASTM Gr. 3    | ≤0.08 | ≤0.015 | ≤0.40 | ≤0.05 | ≤0.5 | — | — |
| ASTM Gr. 4    | ≤0.08 | ≤0.015 | ≤0.20 | ≤0.05 | ≤0.40 | 5.5–6.75 | 3.5–4.5 |
| Ti–Al–V alloy | ASTM Gr. 5 | ≤0.08 | ≤0.015 | ≤0.20 | ≤0.05 | ≤0.40 | 5.5–6.75 | 3.5–4.5 |
| ASTM Gr. 23   | ≤0.08 | ≤0.0125 | ≤0.13 | ≤0.03 | ≤0.25 | 5.5–6.5 | 3.5–4.5 |
Table 2 Some examples of the upgrading process for titanium metal investigated in previous studies²,⁶–⁴⁸

| Method                          | Reference                  | Advantages (deox. limit) | Disadvantages                                      |
|---------------------------------|----------------------------|--------------------------|----------------------------------------------------|
| **Deoxidation (Deox.)**        |                            |                          |                                                    |
| Deox. by M/MOX eq. (DOSS process) | Ono and Miyazaki,⁶ Fisher,⁷–¹⁰ Okabe et al.,¹¹–¹⁴ Oh et al.,¹⁵,¹⁶ Roh et al.¹⁷ | Ti powder can be deoxidized. (~500 ppm O) | Low capability of deox. |
| Calcium halide flux deox.       | Okabe et al.¹⁸–²⁰           | High capability of deox. (~50 ppm O) | Not suitable for removing large amounts of O. Leaching of molten salt bath is needed |
| Electrochemical deox.           | Okabe et al.,²¹,²² Nakamura et al.,²³ Hirota et al.,²⁴ Taninouchi et al.²⁵ | Ultra-high capability of deox. CaCl₂ bath (<10 ppm O), MgCl₂ bath (<100 ppm O) | Long processing time |
| FFC process                     | Chen et al.,²⁶–²⁸ Fray,²⁹ Mohandas and Fray,³⁰ Tripathy et al.³¹ | Production of low-oxygen titanium directly from oxides | Long processing time |
| OS process                      | Ono and Suzuki,³² Suzuki et al.³³–³⁷ | Production of low-oxygen titanium directly from oxides | Long processing time |
| Deox. during EB remelting with Al VIM with CaAl₂ | Yahata et al.³⁸ Rotmann et al.² | Short processing time (~100 ppm O) | Excess Al is contained in Ti |
| PESR with Ca and CaF₂ flux      | Reitz et al.³⁹             | Short processing time (~1500 ppm O) | Capability of deox. is insufficient |
| Electric arc remelting under H₂–Ar atmosphere | Su et al.⁴⁰ | Short processing time (~250 ppm O) | Subsequent VAR is required to remove residual Ca. Applicability to deoxidation of pure Ti is uncertain |
| Deox. of Ti alloy by HDH         | Oh et al.,¹⁶ Roh et al.¹⁷ | Simple process            | Capability of deox. is insufficient |
| **Others**                      |                            |                          |                                                    |
| Electrorefining in molten salt   | Nettle et al.,⁴¹ Suchkov et al.,⁴² Takeuchi et al.⁴³,⁴⁴ Hashimoto et al.,⁴⁵–⁴⁷ Miyazaki et al.⁴⁸ | Almost all impurities can be removed | Contamination from molten salt. Difficulty of morphology control of Ti deposition |
Table 3  Some representative results for titanium deoxidation using various solid state deoxidation techniques

| Method               | Oxygen (mass ppm) | Nitrogen (mass ppm) | Note and references | Exp. no. |
|----------------------|-------------------|---------------------|---------------------|----------|
| Ca-CaO               | 430 → 460         | 20 → 340            | 1273 K, 86 ks, ref. 11 |
| Y-Y$_2$O$_3$         | 200 → 120         | N.A.$^f$            | 1231 K, 260 ks, ref. 12 |
| Y-Y$_2$O$_3$         | 1100 → 150, 170   | N.A.$^f$            | 1213 K, 551 ks, ref. 14 |
| Y-Y$_2$O$_3$         | 210 → 90          | 10 → (30)           | 1173 K, 518 ks, ref. 14 |
| Y-Y$_2$O$_3$         | 950 → 100, 220    | 20 → (50)           | (#T) |
| Y-Y$_2$O$_3$         | 670 → 80, 100     | 30 → (60)           | (#U) |
| Ca-Y-Y$_2$O$_3$      | 210 → 130         | 10 → (40)           | 1173 K, 604 ks, ref. 14 |
| Ca-Y-Y$_2$O$_3$      | 950 → 60, 90      | 20 → (50)           | (#W) |
| Ca-Y-Y$_2$O$_3$      | 670 → 60, 90      | 30 → (120)          | (#T) |
| Ca-CaCl$_2$          | 130 → 16          | 10 → 41             | 1273 K, 90 ks, ref. 19 |
| Ca-CaCl$_2$          | 130 → 17          | 10 → 34             | (#17B1) |
| Ca-CaCl$_2$          | 130 → 35          | 10 → 49             | 1373 K, 40 ks, ref. 19 |
| Ca-CaCl$_2$          | 130 → 22          | 10 → 45             | (#19B1) |
| Ca-CaCl$_2$          | 150 → 62          | 10 → 86             | 1273 K, 86 ks, ref. 19 |
| Electrochem. (CaCl$_2$)$_b$ | 900 →<10       | 40 → 20             | 1223 K, 22 ks, ref. 21 |
| Electrochem. (CaCl$_2$)$_b$ | 1400 →<10      | 20 → 20             | (#49, contaminated by carbon) |
| Electrochem. (CaCl$_2$)$_b$ | 110 → 10         | <10 → <10           | 1223 K, 27 ks, ref. 23 |
| Electrochem. (CaCl$_2$)$_b$ | 900 → 20         | 30 → 50             | (#69, carbon: 20 → 30, 50 → 80 ppm) |
| Electrochem. (CaCl$_2$)$_b$ | 210 → 40, 50     | 10 → 10             | 1189 K, 36 ks, ref. 24 |
| (O in Gd: 2100 → 10, 50 ppm, O in Tb: 2600 → 20, 20 ppm, O in Dy: 2300 → 20, 30 ppm O in Er: 2800 → 40, 40 ppm, O in Y: 11200 → 340, 380 ppm) |
| Electrochem. (MgCl$_2$)$_b$ | 110 → 100        | <10 → 40            | 1173 K, 86 ks, ref. 23 |
| Electrochem. (MgCl$_2$)$_b$ | 900 → 60         | 30 → 70             | (#75, carbon: 20 → 50, 50 → 120 ppm) |
| Electrochem. (MgCl$_2$)$_b$ | 840 → 90          | 20 → 440            | 1173 K, 86 ks, ref. 25 |
| Electrochem. (MgCl$_2$)$_b$ | 1200 → 270        | 40 → 260            | 1173 K, 86 ks, ref. 25 |
| (D13_150121g)        |                   |                     |                    |
| (D15_150123h)        |                   |                     |                    |

$^a$ “M-MO$_x$”: deoxidation by metal/metal oxide, “Ca-CaCl$_2$”: calcium-halide flux deoxidation, “Electrochem.”: electrochemical deoxidation. $^b$ Salt in parentheses shows molten salt used for electrochemical deoxidation. $^c$ Values in parenthesis include uncertainties. $^d$ Residual resistivity ratio, $\rho_{300}/\rho_{4.2}$, determined by measurement at 298 and 4.2 K. $^e$ Vickers micro hardness (kg f mm$^{-2}$), measured using 500 g load at room temperature. $^f$ “N.A.”: not analyzed or not reported. $^g$ Ti wire (φ1.0 mm) was used as sample. Oxygen and nitrogen contents were analyzed by KOBELCO Research Institute, Inc. $^h$ Ti rod (φ3.0 mm) was used as sample. Oxygen and nitrogen contents were analyzed by KOBELCO Research Institute, Inc.
Principle

Because the principle of electrochemical deoxidation of Ti has been reported in detail previously,\textsuperscript{5,21} the deoxidation process is only briefly outlined here. A solid Ti–O solution is deoxidized by Mg in the following reaction:

\[ \text{O (in Ti) + Mg (in flux) = MgO (in flux)} \]  \hspace{1cm} (1)

The equilibrium O concentration in Ti depends thermodynamically on the temperature \( T \) according to the following equation,

\[ \text{[mass\% O] = } (a_{\text{MgO}}/a_{\text{Mg}})(1/f_O)\exp(DG^c/RT) \]  \hspace{1cm} (2)

where \( DG^c \) is the standard Gibbs free energy change associated with the reaction described by eqn (1), \( a_{\text{MgO}} \) and \( a_{\text{Mg}} \) are the activities of MgO and Mg, respectively, and \( f_O \) is the activity coefficient of O in solid Ti.

Fig. 2 shows the binary phase diagram for the Ti–O system.\textsuperscript{49} The equilibrium O concentration of Ti under Mg/MgO equilibrium at 1273 K is plotted as an open circle. For reference, the equilibrium O concentration of Ti under Ca/CaO equilibrium at 1273 K is plotted as a filled circle (about 0.05 mass\% O). The equilibrium O concentration under Mg/MgO equilibrium is approximately 2.6 mass\% (7.4 mol%) at 1273 K. This shows that it is thermodynamically difficult to remove O directly from Ti to levels below 1 mass\% by Mg deoxidant when the activity of MgO (\( a_{\text{MgO}} \)) is high.

The O potentials of \( \beta \)-Ti–O solid solution at temperatures between 1173 and 1473 K have been determined,\textsuperscript{11} and the feasibility of preparing low-O Ti by decreasing the activity of the by-product CaO (\( a_{\text{CaO}} \)) has been examined using various Ca-halide fluxes in the presence of Ca metal (Ca-halide flux deox. shown in
Several factors have been considered in selecting a flux for deoxidation. CaCl₂ has been found to be the most desirable flux at temperatures of ≈1300 K because the deoxidation product CaO dissolves easily in CaCl₂ flux, which decreases its activity and thus lowers the limit of deoxidation. By submerging Ti wires and small pieces in Ca-saturated CaCl₂, Ti samples has been deoxidized to a level of 50 mass ppm (see also Table 3).

In the Ca-halide flux deoxidation method, the ultimate limit of deoxidation depends on the final O concentration in the flux, which means that the purity of the flux and the initial O content of the Ti will rule the deoxidation limit. To decrease the deoxidation limit set by aₘgO, an electrochemical method was developed (electrochemical deox. shown in Table 2). The modified Ca-halide flux deoxidation method is characterized by both the production of Ca from the CaCl₂ flux and the effective removal of O²⁻ (present as CaO) dissolved in the flux by electrochemical means. In this method, as expressed in eqn (3), a Ti cathode is deoxidized by Ca, which forms electrochemically on the surface of the cathode according to eqn (4). O²⁻ species in the flux are carried continuously to the C anode, and O in the flux is removed from the system as CO (or CO₂) gas by the anodic reaction expressed in eqn (5).

\[
\begin{align*}
\text{O (in Ti) + Ca (in flux) = Ca}^{2+} \text{ (in flux) + O}^{2-} \text{ (in flux)} & \quad (3) \\
\text{Ca}^{2+} \text{ (in flux) + 2}e^- = \text{Ca (on Ti cathode: in flux)} & \quad (4) \\
\text{O}^{2-} \text{ (in flux) + C (C anode) = CO (gas) + 2}e^- & \quad (5)
\end{align*}
\]

Unlike the Ca-halide flux deoxidation, the electrochemical method does not require the addition of metallic Ca as a deoxidant, because the activity of Ca near the cathode can be increased by controlling the applied voltage between the Ti cathode and the C anode. In some cases, Ca is precipitated on the cathode using an applied voltage exceeding the theoretical decomposition voltage of CaCl₂ (3.25 V at 1223 K). Furthermore, CaCl₂ flux can be purified through pre-electrolysis. This electrochemical method therefore has the advantage that contamination-free Ca deoxidant and CaCl₂ flux can be used in the deoxidation process. By applying the electrochemical technique to molten CaCl₂, Ti containing O below 10 mass ppm has been successfully produced under certain conditions.

In this study, the feasibility of the electrochemical deoxidation technique using MgCl₂ as flux was examined. A schematic of the electrochemical deoxidation of Ti in molten MgCl₂ is shown in Fig. 3.

\[
\begin{align*}
\text{O (in Ti) + Mg (in flux) = Mg}^{2+} \text{ (in flux) + O}^{2-} \text{ (in flux)} & \quad (6)
\end{align*}
\]

Based on the thermodynamic calculation shown in Fig. 4 when aₘgO is decreased to the level of 10⁻² in the presence of metallic Mg at 1200 K, the chemical potential of O₂ (pO₂) in the system is decreased to ≈10⁻⁴⁵ atm, and Ti containing 0.018 mass% (180 mass ppm) O can be obtained. In other words, when Ti is deoxidized down to commercial O levels for high-grade Ti (0.05 mass% O, or 500 mass ppm) using Mg as reductant, aₘgO at 1200 K must be decreased to the level of 0.025.
Experimental procedure

Fig. 5 shows a flowchart of the experimental procedure for the electrochemical deoxidation of Ti in MgCl₂. A schematic of the experimental apparatus used for...
the electrochemical deoxidation of Ti in MgCl₂ is shown in Fig. 6. Ti in the form of small pieces and wires with different O concentrations and configurations was used as the starting material. The flux was reagent-grade anhydrous MgCl₂ (>97.0%) in flake form, dried at 523 K for more than 43 ks (12 h).

The dehydrated MgCl₂ flux was contained in a Ti or mild steel crucible (89 mm in diameter, 200 mm in height) and set in a gas-tight stainless steel chamber, as shown in Fig. 6. The Ti cathode consisted of several strands of Ti wire ~50 mm in length and 1 mm in diameter. The total electrode surface area was approximately 1000 mm². In the same experiment, a Ti rod (approximately 30 mm in length, 3 mm in diameter) was used as the cathode. High-purity (99.9%) graphite was used as the C anode (approximately 35 mm in length, 3 or 6 mm in diameter). These electrodes, as well as thermocouple tubing, were inserted into the reaction tube through a gas-tight water-cooled stainless steel head.

After the assembled cell was evacuated at ~673 K to ensure a completely gastight and moisture-free system, Ar was introduced to the reaction tube. The furnace was then heated to a constant temperature between 1100 and 1173 K. After the MgCl₂ was melted, the graphite anode was inserted into the molten salt,
and pre-electrolysis was conducted. In the pre-electrolysis, a 2 A current was passed for \( \sim 3.6 \) ks (1 h) between the Ti crucible (or Ni electrode immersed in molten salt) and the C anode to eliminate residual metal and gaseous impurities in the molten salt. Approximately 50 g of silver was placed at the bottom of the crucible to absorb the magnesium metal deposited during electrolysis. The temperature of the molten salt was measured directly using a chromel–alumel thermocouple protected by a stainless steel sheath. After pre-electrolysis, the Ti cathode containing the Ti samples was inserted into the molten \( \text{MgCl}_2 \), and deoxidation experiments were performed by applying voltages between 0 and 3.1 V between the electrodes, which were separated by a distance of \( \sim 30 \) mm. In most cases, the deoxidation of the Ti cathode occurred with the application of voltages exceeding 2.6 V at 1100–1173 K for longer than 22 ks (6 h).

Before and after the pre-electrolysis of \( \text{MgCl}_2 \) and the deoxidation experiments, the electrochemical properties of the flux were measured by cyclic voltammetry (CV). An electrochemical interface (Solartron SI1287) was used for the CV measurements.

After the deoxidation experiment, the electrodes were removed from the molten \( \text{MgCl}_2 \), and the cell was cooled in a stream of Ar gas. In some cases, only the Ti cathode was replaced after cooling for the next experimental run. The fused salt that adhered to the surface of the Ti electrode was removed by leaching with \((1 + 1)\) acetic acid, after which the Ti samples of the electrode were carefully
cleaned in (1 + 10) aqueous HCl solution, followed by water, alcohol, and acetone, and then dried.

The Ti samples obtained were subjected to O and N analyses using LECO analyzers. Prior to the analyses, the samples were surface-etched with a 1 : 4 : 10 mixture of HF–HNO₃–H₂O. To increase the accuracy of the O and N analyses, 1.1 g of nickel capsule containing 8.8 ± 1.4 μg O and 0.2 ± 0.2 μg N was used as an extraction bath for each 0.05–0.1 g Ti sample. The instrument for the O analysis was calibrated using Ti standard samples containing 470 ± 30 and 980 ± 40 mass ppm O.

Results and discussion

Fig. 7(a) shows the CV of the MgCl₂ salt at 1173 K using a Ni quasi-reference before pre-electrolysis. The deposition of Mg occurs at approximately −0.7 V with respect to the Ni quasi-reference, and gas evolution occurs at approximately +1.6 V. The

![Cyclic voltammograms in MgCl₂ molten salt at 1173 K. Surface area of electrode: 2 cm² (C rod, Ni rod). Surface area of electrode: 260 cm² (Ti crucible). Scan rate: 100 mV s⁻¹. (a) Before pre-electrolysis. (b) After pre-electrolysis. (c) After electrolysis for Ti deoxidation.](image-url)
oxidation wave between 1 and 1.6 V probably results from oxygen impurities in the molten salt, and the gas evolution peak at ~1.6 V corresponds to the evolution of Cl₂ gas.

During pre-electrolysis using a Ni electrode as a cathode, Mg metal was electrochemically deposited on the Ni electrode. After pre-electrolysis, the Mg deposition and gas evolution peaks shifted to 0 and 2.3 V, respectively. Fig. 7(b) and (c) show the CV of the molten MgCl₂ before and after the deoxidation experiments. As the theoretical decomposition voltage of MgCl₂ at 1173 K is 2.3 V, the reference electrode worked correctly, and the Ni quasi-reference electrode became a reference for Mg/Mg²⁺ after pre-electrolysis.

The results shown in Fig. 7 indicate that the electrochemical properties of MgCl₂ are unchanged before and after the deoxidation experiments. After pre-electrolysis, only the Mg deposition wave and Cl₂ evolution are observed, and therefore, the reaction system in the molten salt can be regarded as contamination-free MgCl₂.

By applying a voltage of ~3.1 V between the electrodes, the chemical potential of metallic Mg (aMg) in MgCl₂ was increased on the surface of the Ti cathode to a value approaching 1, and the Ti samples were deoxidized by the electrochemically produced Mg. The resulting O species, present mainly as O²⁻ dissolved in the molten MgCl₂, reacted at the C anode to form CO (or CO₂) gas, which was removed from the molten salt system. For example, after electrochemical deoxidation at 1173 K for 86 ks, Ti wires 1.0 mm in diameter and containing 0.084 mass % (840 mass ppm) O were deoxidized to 0.009 mass% (90 mass ppm) (Exp. no. D13_150121 shown in Table 3). When a Ti rod of 3.0 mm diameter containing 0.12 mass% (1200 mass ppm) O was deoxidized at 1173 K for 86 ks, Ti with 0.027 mass% (270 mass ppm) O was obtained (Exp. no. D15_150123 shown in Table 3). The N concentration in the sample was increased from ~10–40 to 40–440 mass ppm after deoxidation.

In Table 3, some representative analytical results for the O and N levels in Ti before and after deoxidation are listed, as well as results from previous studies. The analytical values below 0.01 mass% (100 mass ppm) listed in the table include some uncertainty because gas analysis of Ti samples below 0.01 mass% (100 mass ppm) is difficult. However, notably, Ti with an oxygen level of about 0.01 mass% (100 mass ppm) was obtained by using Mg as the deoxidant when using the electrochemical technique.

Table 4 summarizes the deoxidation limits for the Mg/MgO, Ca/CaO, and Y/Y₂O₃ systems. The activity of the metal oxides for obtaining Ti with 100 mass ppm O when using the respective metal deoxidants was calculated using the available thermodynamic data and are listed in the table. In this study, Ti wires containing 0.12 mass% (1200 mass ppm) O were deoxidized to less than 0.02 mass% (200 mass ppm) O. In some cases, the O concentration in the Ti samples was reduced to below 0.01 mass% (100 mass ppm) O, which cannot be accomplished using the current Kroll process. These experimental results show that the activity of MgO, aMgO, was decreased to below 0.01.

When electrolysis in CaCl₂ is utilized to remove O directly from Ti, the deoxidation limit can be easily decreased to below 0.01 mass% (100 mass ppm). However, after deoxidation, CaCl₂ flux attached on the surface of Ti products must be removed by dissolving in aqueous solution, which causes O pickup. It is
impractical to remove CaCl$_2$ by evaporation, because the vapor pressure of CaCl$_2$ is low even at elevated temperatures. Fig. 8 shows the temperature dependence of the vapor pressures of CaCl$_2$ and MgCl$_2$.\textsuperscript{50} The vapor pressure of MgCl$_2$ is two or three orders of magnitude higher than that of CaCl$_2$. The high vapor pressure of MgCl$_2$ might enhance operational challenges during electrolysis.\textsuperscript{51} However, MgCl$_2$ can be removed directly from titanium products by vacuum treatment; a technique for MgCl$_2$ removal \textit{via} vacuum distillation is already established in the Kroll process. This MgCl$_2$ removal technique can easily be applied to the deoxidation process investigated in this study.

Fig. 9 shows the new recycling process for Ti scrap using electrochemical deoxidation in molten MgCl$_2$ followed by the removal of MgCl$_2$ by vacuum distillation. The reduction chamber used in the conventional Kroll process can be utilized in the electrochemical deoxidation process, as schematically shown in

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**Table 4** Equilibrium oxygen concentrations calculated under M/\(\text{MO}_x\) equilibrium at 1273 K using available thermodynamic data.\textsuperscript{11,50} Calculated activities of metal oxides (\(a_{\text{MO}_x}\)) used to obtain low-oxygen-containing titanium (100 and 1000 mass ppm O) are also shown for reference.

| System   | Equilibrium O conc. in Ti at 1273 K, \(C_{\text{O,eq}}\) (mass ppm) | Required \(a_{\text{MO}_x}\) to obtain Ti with 1000 ppm O at 1273 K, \(a_{\text{MO}_x}\) | Required \(a_{\text{MO}_x}\) to obtain Ti with 100 ppm O at 1273 K, \(a_{\text{MO}_x}\) |
|----------|-------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| Mg/MgO   | 26 000                                                            | 0.039                                                          | 0.0039                                                          |
| Ca/CaO   | 500                                                               | 2.0                                                             | 0.20                                                            |
| Y/YO$_{1.5}$ | 180                                                            | 13                                                              | 0.41                                                            |

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**Fig. 8** Vapor pressures of metal chlorides as functions of reciprocal temperature.\textsuperscript{50}
Fig. 10. As Ti production is increased, scrap treatment becomes increasingly important. In the future, the direct O removal technique proposed in this study may be applied to recycling Ti scrap.

Fig. 9 Recycling process proposed in this study. Oxygen dissolved in Ti scrap is directly removed by molten salt electrolysis in MgCl₂.

Fig. 10. Industrial application of the recycling process based on electrolysis in MgCl₂. Process is feasible in existing Ti smelters based on the Kroll process.
Conclusions

The removal of O from Ti using an electrochemical technique in molten MgCl₂ was examined at temperatures of ~1173 K. The activity of Mg was increased near the Ti cathode surface and the activity of MgO was decreased by applying voltages between the Ti cathode and C anode immersed in molten MgCl₂. These activity changes facilitated the deoxidation of a Ti cathode consisting of the Ti samples. A Ti sample containing approximately 1000 mass ppm O were deoxidized to less than 200 mass ppm by applying 3.1 V between the Ti and C electrodes for 86 ks. In some cases, the O concentration in Ti was decreased to below 100 mass ppm, which cannot be accomplished using the conventional Kroll process. The application of this deoxidation technique to industrial recycling processes may become practical in the future.

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