Chemical-Hydrothermal Synthesis of Bioinert Oxide Films on Ti Substrates

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Titanium and its alloys have been employed in bone plates + screws and these are normally designed to be removed after the patient has recovered. However, bone can sometimes attach to the surface of implanted materials that remain in the body for long periods of time. This can lead to re-fracture of newly repaired bone during operations to remove the implants. The purpose of the present study was to synthesise bioinert films, including ZrO₂ on pure Ti surfaces and to study apatite (HAp) formation on the synthesised oxide films in Hanks' solution. Commercial purity Ti disks were chemically treated with H₂O₂/HNO₃ aqueous solutions at 353 K for 20 min. The disks were hydrothermally treated with ZrOCl₂/NH₄Cl aqueous solutions in a Teflon-lined autoclave at 453 K for 12 h. The specimens were immersed in Hanks' solution, which was maintained at 310 K. After being soaked for different periods of time, the surfaces were observed by SEM. In the hydrothermal treatment with ZrOCl₂/NH₄ aqueous solution, the surface product was anatase-type TiO₂. On the other hand, when citric acid was added, the surface of Ti was covered homogeneously with a ZrO₂-TiO₂ composite film. Some of the Zr(OH)₄ sol in the solution is thought to have dissolved into the solution by coordinate binding with citric acid carboxyl groups, leading to precipitation of ZrO₂ in the TiO₂ or on its surface. The ZrO₂-TiO₂ film suppressed the precipitation of HAp on the surface in the SBF soaking. A bioinert ZrO₂-TiO₂ composite film could be synthesised on Ti surfaces by a combined chemical-hydrothermal treatment. This method offers excellent potential for inhibiting direct bonding to living bone, and can be applied to assist the removal of implants made from existing Ti alloys.

Keywords: Biomaterials, bioinert, zirconia (ZrO₂), surface modification, hydrothermal treatment, apatite

1. Introduction

Titanium and its alloys have been used widely as biomaterials for orthopaedic and dental implants because of their excellent mechanical properties and bio-compatibility. These alloys have also been employed in bone plates/screws, and these are normally designed to be removed after recovery. Bone is known to bond to the surface of Ti and Ti alloys. This can lead to re-fracture of newly repaired bone during operations to remove the implants.

Recently, Zr-based alloys have received considerable attention in the field of biomaterials because these alloys do not bond directly to living bone. The inhibition of bone conduction on the surface of Zr-based alloys is thought to be due to the presence of a thin layer of zirconia (ZrO₂) on the surface. Zr-based alloys are at an early stage of development for biomedical applications. In contrast, there is a substantial amount of literature on Ti-based alloys in biomedical field. If bioinert films can be synthesised on Ti-based alloys, their field of application will be further extended.

Ceramic films are generally deposited on substrates by methods such as thermal oxidation, plasma spraying and sol-gel processing. Although these conventional methods are well established, the coating process is generally carried out at temperatures higher than 773 K, which can degrade the mechanical properties of Ti-based alloys.

Recently, we succeeded in synthesising bioactive oxide films, such as titanium dioxide (TiO₂) and calcium titanate (CaTiO₃), on Ti and its alloys using a modified chemical-hydrothermal treatment. In addition to synthesising bioactive oxide films, we could synthesise bioinert ZrO₂-TiO₂ composite films on pure Ti substrates by a hydrothermal treatment with Zr(OH)₄ gel dispersed ammonia/lactic acid solution. The carboxyl group in lactic acid is conjectured to contribute to activate the surface of Zr(OH)₄. As a result, it contributes to involve ZrO₂ into TiO₂.

The purpose of the present study was to synthesise bioinert films, including ZrO₂ on pure Ti surfaces by a modified chemical-hydrothermal treatment using citric acid. In addition, apatite (HAp) formation on the synthesised oxide films in Hanks' solution was also investigated.

2. Experimental Procedure

Commercially pure Ti disks (Ø 6 mm × 2 mm) were cut from a rod and mechanically polished with 400-1500 emery papers and 0.3 µm alumina paste. The specimens were ultrasonically washed with acetone and distilled water, and then dried. The chemical treatment was carried out with 5 M H₂O₂/0.1 M HNO₃ aqueous solutions (2.5 mL for each specimen) at 353 K for 20 min. The disks were then placed into a Teflon-lined autoclave with an internal volume of 100 mL (eight disks per batch), which was filled with 100 mM ZrOCl₂/5 M NH₄Cl aqueous solutions up to 50% volume. Citric acid is a hydroxyl fatty acid, which has three times as many carboxyl groups as lactic acid.

Hanks' solution with ion concentrations (Na⁺ 142.0, K⁺ 5.8, Mg²⁺ 0.9, Ca²⁺ 1.3, Cl⁻ 145.6, HCO₃⁻ 4.2, HPO₄²⁻ 8.3, SO₄²⁻ 4.2 mM) similar to those of human blood plasma, was employed as a simulated body.
3. Results and Discussion

3.1 Surface Modification

Figure 1 shows the morphologies of surface-modified specimens. Although the image is not shown here, the surface shows a sponge-like morphology after the chemical treatment\(^\text{10}\). Following hydrothermal treatment with the aqueous solution without citric acid, cubic crystals were formed homogeneously over the surface (Figure 1(a)), in a similar manner to that obtained by the hydrothermal treatment with aqueous NH\(_3\). However, a uniform layer of very fine crystals was formed on the surface of the specimen subjected to the hydrothermal treatment with citric acid at C\(_{\text{Ca}}\) = 400 (Figure 1(b)). A similar morphology was also obtained at C\(_{\text{Ca}}\) = 200, but crystals were coarser at C\(_{\text{Ca}}\) = 600. Thus, the morphology was drastically changed by the addition of citric acid to the ZrOCl\(_2\)/NH\(_3\) solution.

Figure 2 shows XRD patterns obtained from the surface products by the combined chemical-hydrothermal treatment. Sharp peaks attributed to anatase-type TiO\(_2\) appeared following the hydrothermal treatment without citric acid. On the other hand, broad peaks corresponding to ZrO\(_2\) can be confirmed to appear in the XRD profile after the treatment with citric acid. Some of the Zr(OH)\(_4\) sol in the solution is thought to have dissolved into the solution by coordinate bonding with citric acid carboxyl groups, leading to precipitation of ZrO\(_2\) in the anatase-type TiO\(_2\) or on its surface. The pH decreased with citric acid addition, which induced broadening of XRD peaks for TiO\(_2\).

Although the XRD peaks attributed to ZrO\(_2\) were very small, XRF peaks from Zr were clearly visible in the specimen synthesised with citric acid added solution as shown in Figure 3. In order to compare the relative volume fraction of ZrO\(_2\) in the surface products, the intensity ratio of the XRF main peak for Zr (Zr L\(_{\text{m}}\)) relative to that for Ti (Ti K\(_{\text{a}}\)) was measured as shown in Figure 4. The intensity ratio I\(_{\text{Zr}}\)/I\(_{\text{Ti}}\) increases drastically by addition of citric acid. The value showed maximum at C\(_{\text{Ca}}\) = 400, TiO\(_2\) is known to slightly dissolve into alkaline solutions. The inclusion of ZrO\(_2\) into the film needs citric acid, but the addition of excess acid seems to suppress the dissolution/re-precipitation of TiO\(_2\). A similar tendency could be also confirmed in a previous study with lactic acid\(^\text{10}\).

![Figure 1. Surface morphologies of product films synthesised by the hydrothermal treatment with (a) 100 mM ZrOCl\(_2\)/5 M NH\(_3\) and (b) 100 mM ZrOCl\(_2\)/5 M NH\(_3\)/400 mM C\(_6\)H\(_{12}\)O\(_7\) aqueous solutions.](image1)

![Figure 2. X-ray diffraction patterns of films on pure Ti substrates hydrothermally synthesised in 100 mM ZrOCl\(_2\)/5 M NH\(_3\) and 100 mM ZrOCl\(_2\)/5 M NH\(_3\)/400 mM C\(_6\)H\(_{12}\)O\(_7\) aqueous solutions.](image2)

![Figure 3. X-ray fluorescence spectrum of film on pure Ti substrates hydrothermally synthesised in 100 mM ZrOCl\(_2\)/5 M NH\(_3\)/400 mM C\(_6\)H\(_{12}\)O\(_7\) aqueous solution.](image3)

![Figure 4. Intensity ratio of Zr to Ti in XRF spectrums and arithmetical mean roughness of films synthesised with 100 mM ZrOCl\(_2\)/5 M NH\(_3\) and 100 mM ZrOCl\(_2\)/5 M NH\(_3\)/400 mM C\(_6\)H\(_{12}\)O\(_7\) aqueous solutions.](image4)
The roughness of surfaces affects several properties including precipitation of HAp and proliferation of cells. Therefore, contact-mode scanning probe microscopy (SPM) was performed to evaluate the surface characteristics in this study. The arithmetical mean roughness of the surfaces, $Ra$, was obtained from the SPM images in an area of $30 \mu m \times 30 \mu m$ using the instrument software. The roughness $Ra$ decreases drastically by addition of citric acid. However, coarsening occurred at $C^A = 600$.

3. 2 Hanks’ Solution Immersion Test

Hanks’ solution was used for bioactivity in vitro testing. After 20 days soaking, broad peaks from the precipitates began to appear in the XRD spectrum in almost all specimens, and they could be assigned to HAp. Figure 5 shows XRD profile of surface precipitate on $\text{ZrO}_2$-$\text{TiO}_2$, synthesised hydrothermally in the aqueous solution of $C^A = 400$ after 20 days soaking in SBF, as an example. The peaks of $\text{ZrO}_2$ can’t be observed but an obvious peak of $\text{Zr}_2(\text{PO}_4)_2$ is confirmed to appear. This phase could be also observed in the specimen of $C^A = 600$.

![Figure 5. X-ray diffraction pattern of surface precipitate on $\text{ZrO}_2$-$\text{TiO}_2$ hydrothermally synthesised in 100 mM $\text{ZrOCl}_2$/$5$ M $\text{NH}_4$/$400$ mM $\text{C}_2\text{H}_5\text{OH}$ aqueous solution after 20 days soaking in SBF.](image)

As mentioned above, it is difficult to determine the beginning of HAp precipitation during the SBF soaking from XRD profiles. Therefore, SEM observations were used to monitor the growth of these precipitates from the incipient stages up to 14 days soaking. Figure 6 shows SEM images of specimens after 4 days soaking in SBF. A thin precipitate is confirmed to form on the surface synthesised with $100$ mM $\text{ZrOCl}_2$/$5$ M $\text{NH}_4$ aqueous solution, $C^A = 0$ (Figure 6(a)). In contrast, no such precipitate can be observed on the surface of $C^A = 400$ (Figure 6(b)). Although the images are not shown here, this surface was also covered with a thin film after 6 days. The film is as yet unidentified, but may be amorphous calcium phosphate or zirconium phosphate. In this paper, such precipitates are also regarded as HAp for the sake of simplicity.

![Figure 6. Surface morphologies of product films synthesised by the hydrothermal treatment with (a) $100$ mM $\text{ZrOCl}_2$/$5$ M $\text{NH}_4$ and (b) $100$ mM $\text{ZrOCl}_2$/$5$ M $\text{NH}_4$/$400$ mM $\text{C}_2\text{H}_5\text{OH}$ aqueous solution after 4 days SBF soaking.](image)

The beginning of HAp precipitation is summarised in Table 1. HAp began to form on the non-modified Ti surface and the $\text{TiO}_2$ synthesised hydrothermally using aqueous $\text{NH}_4$ after 5 days and 4 days immersion, respectively. HAp was confirmed after 4 days on the $\text{TiO}_2$ at $C^A = 0$. Although the precipitation was promoted at $C^A = 0$ compared to non-modified $\text{Ti}$, the onset was clearly delayed by addition of citric acid. On the surfaces treated with the solutions of $C^A = 400$ and 600, the precipitates can be confirmed after 5 and 8 days, respectively. The HAp formation was suppressed on the surfaces though main constituent of the surfaces was $\text{TiO}_2$, which is known to promote the deposition of HAp. This suppression of HAp formation is probably due to $\text{ZrO}_2$ in the $\text{TiO}_2$. Furthermore, fine complex surface structures have been reported to promote the deposition of HAp during SBF soaking in $\text{TiO}_2$. In fact, rapid precipitation of HAp could be confirmed on the $\text{TiO}_2$ with fine morphology, which was hydrothermally synthesised with distilled water. This needed only 2 days for formation of HAp thin film on the surface. The present $\text{TiO}_2$ at $C^A = 200$ and 400 show similar morphologies. Therefore, it might be concluded that the small volume fraction of $\text{ZrO}_2$ is effectively working to suppress HAp formation. A peak of $\text{Zr}_2(\text{PO}_4)_2$ appears in the XRD profile (Figure 5), and it is hypothesised that this phase may suppress the deposition of HAp on the surfaces during SBF immersion.

### Table 1. Summary of SBF immersion tests. “P” shows the beginning of the HAp precipitation determined by SEM observation

<table>
<thead>
<tr>
<th>Samples</th>
<th>Soaking period in SBF</th>
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<tbody>
<tr>
<td>$C^A$/mM</td>
<td>2d</td>
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<tr>
<td>0</td>
<td>P</td>
</tr>
<tr>
<td>200</td>
<td>P</td>
</tr>
<tr>
<td>400</td>
<td>P</td>
</tr>
<tr>
<td>600</td>
<td>P</td>
</tr>
<tr>
<td>$\text{TiO}_2$</td>
<td>P</td>
</tr>
<tr>
<td>Pure Ti</td>
<td>P</td>
</tr>
</tbody>
</table>

It can be concluded that the present films containing $\text{ZrO}_2$ suppress HAp precipitation regardless of the
fine morphology. Thus, this surface modification has considerable potential for suppressing direct bonding to living bone, and it is expected to be applicable to easily removable implants made from existing Ti alloys.

4. Conclusions

The synthesis of bioinert ZrO$_2$-TiO$_2$ films on Ti surfaces by a combined chemical-hydrothermal treatment and the formation of HAp on these surfaces during SBF soaking were investigated. The following conclusions were reached:

1) ZrO$_2$-TiO$_2$ composite films could be synthesised on Ti surfaces by hydrothermal treatment with ZrOCl$_2$/NH$_3$/C$_6$H$_5$O$_7$ (citric acid) aqueous solution after chemical treatment with H$_2$O$_2$/HNO$_3$ aqueous solution. Some of the Zr(OH)$_4$ sol in the solution is thought to have dissolved into the solution by coordinate bonding with citric acid carboxyl groups, leading to precipitation of ZrO$_2$ in the TiO$_2$ or on its surface.

2) The ZrO$_2$-TiO$_2$ films suppressed the precipitation of HAp on the surfaces regardless of the fine morphology. Therefore, this method has potential for inhibiting direct bonding to living bone, and can be applied to easily removable implants made from existing Ti alloys.

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REFERENCES

6) M. Niinomi, J. the Mechanical Behavior of Biomedical Materials 2008;1; pp. 30-42.