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Original Article

Optimum temperature and chlorine ion concentration for hydrogen peroxide treatment of titanium dental implant material

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ABSTRACT

Hydrogen peroxide treatment is a cost-effective and simple method to improve the bioactivity of titanium implants. In this study, the effects of chloride ion concentration and temperature of hydrogen peroxide on the surface treatment of titanium were investigated using X-ray diffractometry (XRD), Field Emission-Scanning Electron Microscopy (FESEM), and tests in order to determine wettability and apatite forming ability. The results showed that at the lower temperatures of treatment (60 °C), hydrogen peroxide corroded the formed titania layer and the post-heat treatment resulted in rutile formation on the surface of titanium. At higher temperatures of treatment (100 °C), a uniform and crack-free anatase layer was formed on the surface of titanium, leading to the improvement of superhydrophilicity and the apatite forming ability of titanium. However, these properties were affected by increasing the chloride concentration of hydrogen peroxide. At appropriate conditions, titanium dental implant surfaces could be treated effectively using hydrogen peroxide, such that the time of treatment could be reduced to 5 h.

1. Introduction

Attractive properties of titanium and its alloys, such as biocompatibility, good corrosion resistance, high strength to weight ratio, low elastic modulus and density, have made them promising candidates for dental implantation. However, titanium behaves as a bioinert material *in vivo* [1]; so, it requires a surface treatment for bioactivation [2]. It is also necessary to improve the cell-implant interaction and the bonding ability of the titanium implants to the surrounding bone [3]. *In-situ* bioactive phase formation on the surface of titanium has been promoted using techniques such as oxidation [4,5], alkali-heat treatment [6] and hydrogen peroxide

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(H_2O_2) treatment [7]. The direct oxidation of titanium at higher temperatures, require more prolonged time of heat treatment with enhanced energy consumption and more chance of microstructural transformation of titanium. Alkali-heat treatment and hydrogen peroxide treatment are performed in a liquid media with the formation of rutile and anatase on titanium surface, respectively.

In addition to the bioactivity of titanium implants, some other parameters such as wettability, surface morphology [8] and cell response need to be considered. This is because hydrophilic surfaces facilitate early protein adsorption, cell-implant interactions and faster bone integration [9].

Tengvall et al. have already reported the surface treatment of titanium using hydrogen peroxide [7]. It has been reported that the surface treatment of titanium using hydrogen peroxide consists of three steps: titanium oxidation, titania gel formation and titanium dissolution [10].

Different values for appropriate time and temperature of hydrogen peroxide treatment are reported by researchers. For example, it has been reported that 15 wt.% of hydrogen peroxide at 60 °C, in the presence of 0.1 M HCl, for 1 h can result in the optimal efficiency [11]. Also, other concentrations of hydrogen peroxide (such as 30 wt.%) have been used to treat the titanium surface for different times up to 48 h at room temperature, resulting in the severe intergranular corrosion of titanium [12].

Wu used the 30% hydrogen peroxide in the presence of different anions (Cl^-, F^- and SO_4^{2-}) at 80 °C for 72 h without any post-heat treatment for the surface treatment of titanium [13]. Our previous study has indicated that hydrogen peroxide treatment of titanium in the presence of Cl^- ion leads to corrosion and reduces the mechanical properties of porous titanium scaffolds [14]. Moreover, chloride ion (at the concentration of 5 mM) was found to improve the wettability of the surface-treated titanium using hydrogen peroxide treatment at 80 °C, than fluoride ion [15].

While several researchers have used different processing temperatures (60 and 80 °C) and ion concentrations, the effect of hydrogen peroxide temperature has not yet been studied comparatively. This study was, therefore, designed to investigate the effect of these two parameters on the surface treatment of titanium using hydrogen peroxide up to the higher temperature of 100 °C.

2. Materials and methods

2.1. *Surface treatment using hydrogen peroxide*

Titanium plates (grade 2, Kobe Steel Company, Japan) were cut to the size of 10 × 10 × 1 mm and polished using the SiC grit number 800 to remove the naturally formed oxide layers. After ultrasonic cleaning of the samples in ethanol and deionizing water for 5 min, each piece of the titanium plates was immersed in 100 ml of the 15 wt.% hydrogen peroxide solution in the presence of different concentrations (0, 3, 6, 12 mM) of chloride ion by using different amounts of NaCl (Merck, CAS No: 7647-14-5, Germany) at 60, 80 and 100 °C for 5 h. The time of immersion was selected based on the results of our experiments and experience. Titanium plates were then taken out and washed gently with deionized water and dried at room temperature for 24 h. This was followed by heating the specimens at 600 °C for 1 h to ensure the crystallization of titania on the surface. Coding of the samples was done based on HHT-X-Y, where HHT refers to hydrogen peroxide and heat treated sample, X refers to the molar concentration of the chloride ion in hydrogen peroxide, and Y stands for the temperature of the hydrogen peroxide bath.

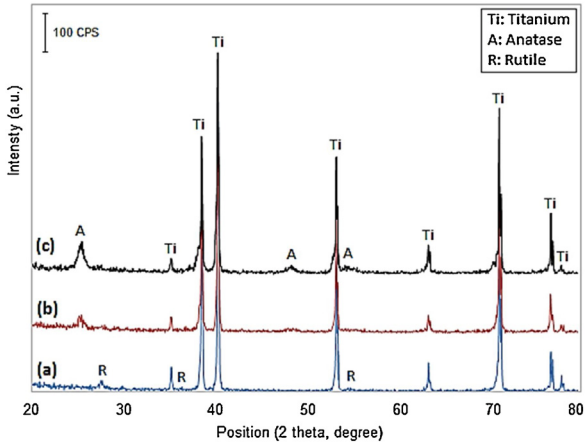

Fig. 1 – X-ray diffraction patterns for: (a) HHT-0-60, (b) HHT-0-80 and (c) HHT-0-100 samples.

2.2. *Characterization of the surface*

To study the phases formed on the surface of the treated titanium samples before and after heat treatment, X-ray diffraction (XRD: Philips, X'Pert MPD) studies were conducted using a Cu–Kα X-ray source (λ = 1.5405 A°), in the range of 2θ = 20–80°, at the rate of 1°/min and with the step size of 0.05°.

To observe the surface morphology of the samples, the treated surfaces were gold-coated using the sputter coater; also, a Field Emission Scanning Electron Microscope (FESEM: TESCAN, MIRA3) was employed, in the secondary electron (SE) mode, at the accelerate voltage of 20 kV and with the beam spot size of 3–5 nm.

For wettability measurements, the static water contact angle technique was used, according to the D7334-08 (2013) ASTM standard. Accordingly, a 4 μl droplet of deionized water was dropped onto the sample surface after heat treatment, using an instrument for contact angle measurement (FACE, CA-D). The shape of the droplet was observed and the contact angle between water and the sample surface was measured (n = 4) using an image analyzer software (ImageJ).

The *in vitro* apatite forming ability of the surface-treated titanium samples was investigated by soaking them in a 20 ml simulated body fluid (SBF) at 37 °C for 7 days, according to the ISO 23317 standard [16] (based on the Kokubo protocol). After taking the samples out of the solution, they were gently washed with double distilled water and dried at room temperature for 24 h. Apatite formation on the surfaces of the immersed samples was studied using the SEM and energy-dispersive X-ray spectroscopy (EDS).

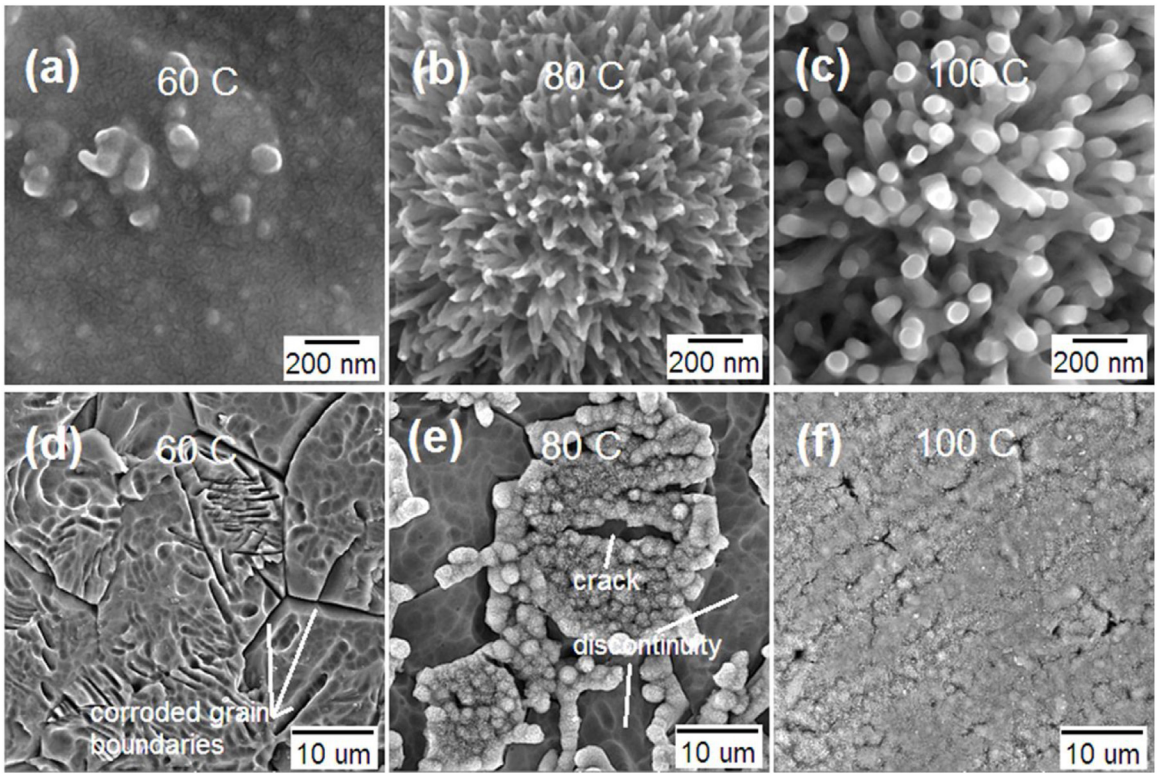

Fig. 2 – FESEM micrographs for: (a) and (d) HHT-0-60, (b) and (e) AH0-80, and (c) and (f) HHT-0-100 samples (at high and low magnifications).

For the L-929 cell attachment ability of surface treated samples (the effect of chlorine concentration), the surface treated titanium samples were sterilized using the 70% ethanol solution. The L-929 cells (mouse fibroblast) were seeded on the samples at a density of 2×10^6 cells/sample and incubated at 37 °C in an incubator for 2 days. The attached cells were then fixed using 2.5% glutaraldehide solution, and this was followed by the dehydration process. The samples were gild coated using the sputter coater and their surfaces were observed using the SEM.

Quantitative data were expressed as mean ± standard deviation. Statistical analysis was performed using IBM SPSS Statistics 23 software, and the P value smaller than 0.05 was considered significant.

3. Results and discussion

3.1. *The effect of hydrogen peroxide bath temperature*

3.1.1. *Phase identification*

According to our previous study [15], the surface of hydrogen peroxide treated titanium showed titania gel at 80 °C for 72 h before heat treatment (the amorphous phase), which was transformed to the crystalline anatase phase after heat treatment.

Fig. 1 presents the X-ray diffraction patterns for the samples treated with hydrogen peroxide for 5 h at various temperatures and then further heat treated. All samples exhibited sharp peaks at 2θ values of 35.09, 38.42, 40.17, 53, 62.95, 70.66, 76.28 and 77.40° (JCPDS No: 00-044-1294), corresponding to titanium. It was evident that HHT-0-80 and HHT-0-100 samples, besides all titanium peaks, exhibited other peaks at 2θ values of 25.32, 48.06 and 53.97° (JCPDS No: 01-086-1157), corresponding to titanium dioxide (anatase). The HHT-0-60 sample, in addition to the titanium peaks, exhibited other peaks at 2θ values of 27.43, 36.08 and 54.32° (JCPDS No: 00-034-0180), indicating the formation of rutile (titanium dioxide).

It was evident that the anatase phase could be formed on the surface of titanium instead of rutile, by raising the temperature of hydrogen peroxide from 60 to 100 °C. Both anatase (TiO_2) and rutile (TiO_2) are bioactive phases [17], and their formation on the surface of the titanium implant can improve the bioactivity of titanium implant *in vivo*, as well as improving the implant-cell or the surrounding tissue interaction. Anatase/rutile formation on the surface of titanium can lead to the better apatite formation and osteointegration of the titanium implant [1]. However, as the thickness of a bioactive phase on the surface of the implant affects its bioactivity behavior *in vivo*, a minimum thickness is required for the optimal performance of the coating [1,18]. The thickness of the titania layer on the hydrogen peroxide treated titanium could be increased from 0.3 to 1 μm by raising the time of treatment from 20 to 60 min [18].

The intensity of anatase peaks for the HHT-0-100 sample was significantly higher than that of the HHT-0-80 sample, indicating a thicker coating of anatase on the surface. It means that by raising the temperature of the hydrogen peroxide bath from 80 to 100 °C, the thickness of anatase at the surface was

increased. On the other hand, by decreasing the temperature of the hydrogen peroxide to 60 °C, only the surface of titanium was corroded [12], and the rutile phase was formed on the surface of titanium through the subsequent heat treatment. These results, therefore, showed that the temperature of the hydrogen peroxide had a significant effect on the type and thickness of the bioactive phase formed on the surface of titanium. This has not been reported previously.

3.1.2. *FESEM observation*

Fig. 2 presents the FESEM micrographs for the samples treated with hydrogen peroxide for 5 h at various temperatures and then further heat treated. Based on our previous study [15], the surface of titanium specimens treated by the hydrogen peroxide solution for 72 h at 80 °C was covered by the flower-like anatase which included a number of broad cracks.

According to Fig. 2(a) and (d), at the surface of the HHT-0-60 sample, no significant oxide particle or any other feature could be observed, while the grain boundaries of titanium were corroded, as observed by other researchers [9,17]. The hydrogen peroxide treatment of titanium at low temperatures could provide some corrosive media [12]. Because of the higher energy of grain boundaries, they are more disposed to corrosion at the corrosive media. Fig. 2(b) and (e) show sharp and narrow nano flower-like wires (30 ± 3 nm in diameter and 210 ± 15 nm in length) on the surface of the HHT-0-60 sample. Major discontinuities and cracks were also seen on the sample surface, even at low magnifications. The coating including surface cracks could decrease the corrosion resistance of the implants, because of the micro galvanic corrosion phenomenon. So, a uniform, crack-free and bioactive coating could be more appropriate for the surface of titanium implants.

Fig. 2(e) suggests that the whole surface of the HHT-0-80 sample had been covered by these nanowires, but a few were mechanically detached during the treatment or post heat treatment. Fig. 2(c) and (f) present the surface morphology of the HHT-0-100 sample. The surface was completely covered by thicker (65 ± 4 nm in diameter) and longer nanowires, with no visible cracks. This indicated that the temperature of hydrogen peroxide is a parameter affecting the type and size of the phases formed on the surface of titanium. In general, surface treatment at a lower temperature can lead to intergranular titanium corrosion, while increasing the temperature results in a more uniform surface reaction and the formation of a crack-free anatase coating on the surface of titanium.

It seems, therefore, that the temperature of hydrogen peroxide affects its function. At fewer temperatures, its corrosive essence was dominant, while at higher temperatures, its oxidative essence was dominant.

3.2. *The effect of chloride ion concentration*

According to the results obtained by the SEM and XRD analyses of surface-treated samples at different temperatures, it could be concluded that the optimum temperature of the hydrogen peroxide bath was 100 °C. At this temperature, a relatively crack-free and thick anatase coating was obtained. This temperature was chosen to study the effect of the chloride ion concentration (0, 3, 6 and 12 mM) on the effectiveness of the hydrogen peroxide treatment.

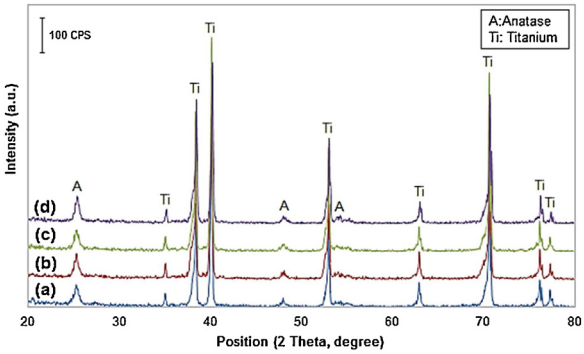

Fig. 3 – X-ray diffraction patterns for: (a) HHT-0-100, (b) HHT-3-100, (c) HHT-6-100, and (d) HHT-12-100 samples.

3.2.1. *Phase identification*

Fig. 3 presents the X-ray diffraction patterns for the surface-treated samples (5 h, 100 °C) at different chloride ion concentrations. No significant difference in the diffraction patterns was observed, such that all patterns showed peaks corresponding to titanium and anatase.

While titanium heat treatment at 600 °C resulted in rutile formation at the surface [4], hydrogen peroxide treatment followed by heat treatment could lead to anatase formation; also, chloride concentration had no significant effect on the phase formation at the surface.

3.2.2. *FESEM observation*

Fig. 4 presents the FESEM micrographs for the surface-treated titanium samples (5 h, 100 °C) at different chloride ion concentrations, after further heat treatment.

However, according to Fig. 4, an increase in the chloride ion concentration led to slight changes in the morphology of anatase and a reduction in the diameter of the nanowires. On the other hand, chloride ion addition had no detectable effect on the phase transformation on titanium surface and only changed the anatase morphology. No crack was detected in the samples HHT-0-100, HHT-3-100, HHT-6-100 and HHT-12-100, showing that the chloride ion concentration had no effect on the coating homogeneity and cracking (this phenomena is more observable in Fig. 6 with lower magnification). Wu added some different anions and cations to the hydrogen peroxide for titanium surface treatment without any post heat treatment [13]. He reported that the function of hydrogen peroxide was affected by anions, and cations were not significantly effective. So, fluorine (NaF and Na_2SO_4) anion could result in anatase formation, chlorine anion (NaCl and HCl) would lead to anatase + rutile formation, and CO_3 anion ($NaCO_3$) might end in amorphous titania formation. Wu showed that crystalline titania nano-rods came into being through a dissolution precipitation mechanism. Actually, titania nano-rods were deposited on the titanium surface through an inhomogeneous nucleation and growth process [13]. While chlorine is an oxidant anion, it could affect the titanium oxidation, titania gel formation and crystallization.

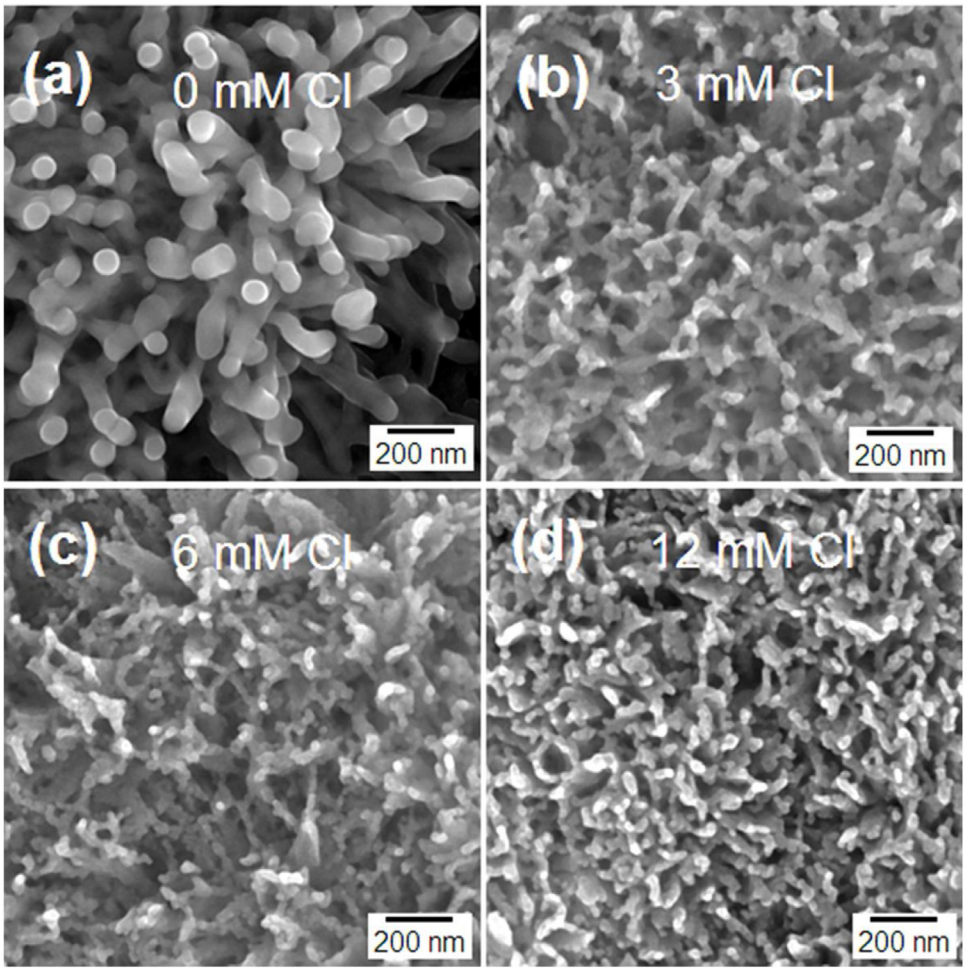

Fig. 4 – FESEM micrographs for: (a) HHT-0-100, (b) HHT-3-100, (c) HHT-6-100 and (d) HHT-12-100 samples.

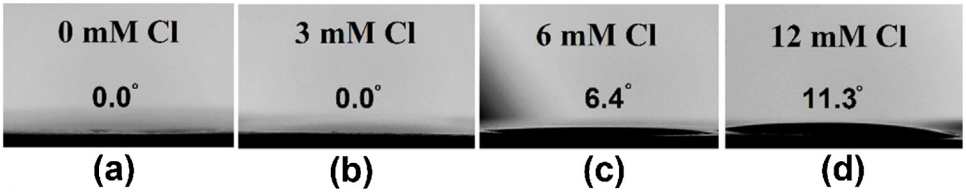

Fig. 5 – Water contact angles for: (a) HHT-0-100, (b) HHT-3-100, (c) HHT-6-100, and (d) HHT-12-100 samples.

3.3. *Wettability measurement*

Fig. 5 presents the results of the wettability measurement for HHT-0-100, HHT-3-100, HHT-6-100 and HHT-12-100 samples. The water contact angles for hydrogen peroxide treated titanium surfaces were $0.0+2.0$, $0.0+2.1$, 6.4 ± 2.5 and 11.3 ± 2.9 for different concentrations of chloride ions (0, 3, 6 and 12 mM), indicating that all these samples were superhydrophilic.

A smaller water contact angle means better wettability as well as more protein and cell adsorption *in vivo* [19]. According to our previous study [4], the water contact angle for the untreated titanium was about 78°, indicating that hydrogen peroxide treatment *via* anatase nanowire formation at the surface of titanium could improve wettability considerably.

3.4. *Apatite forming ability*

Anatase is a bioactive phase facilitating the formation of apatite. However, a minimum thickness of anatase is required on the surface of titanium for aiding apatite formation [1,18]. Also, the surface morphology and porosity of anatase can have a significant effect on its apatite forming ability. Dense anatase has an inferior apatite forming ability in comparison to the porous one [18,20]. The surface energy and surface charge are also important parameters influencing the apatite forming ability and bone formation on the titanium surface [21]. Fig. 4 shows different morphologies of anatase on the surface of titanium, thereby suggesting that the apatite forming ability varied with chloride ion concentration. Fig. 6 presents

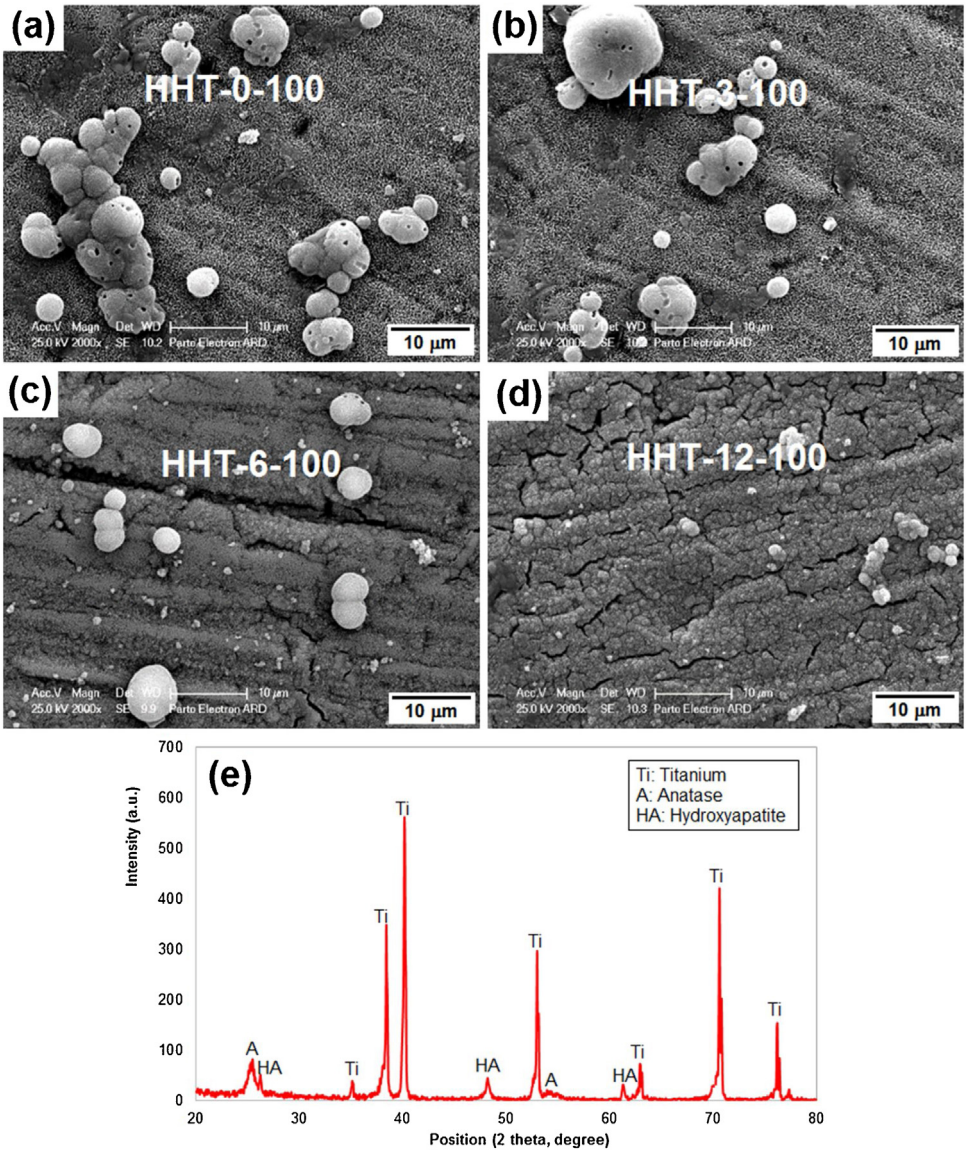

Fig. 6 – Apatite formation on: (a) HHT-0-100, (b) HHT-3-100, (c) HHT-6-100, (d) HHT-12-100, and (e) XRD analysis of apatite particles on the HHT-0-100 sample.

the amount and morphology of the deposited apatite crystals on the surface of the immersed samples by SBF at 37 °C for 3 days, showing that all treated samples exhibited the apatite forming ability. However, it could be seen that fewer apatite particles were formed at the surface of titanium with increasing the chloride concentration. Chloride ion concentration had a significant effect on the bioactivity of the hydrogen peroxide treated titanium. Further, XRD analysis of the surface (Fig. 6(e)) revealed the presence of hydroxyapatite on the surface of the sample HHT-0-100 after immersion in SBF. The inferior apatite forming ability of HHT-12-100, in comparison to HHT-0-100, could be due to the residual sodium and chloride ions (from NaCl) in between the anatase nanowires (Fig. 6(e)).

The morphology and orientation of the anatase/rutile growth could affect the apatite forming ability [1]. It has been concluded that in addition to the minimum thickness requirement (for anatase or rutile) for apatite formation, crystallographic relationships should also be favorable. As shown in Fig. 3, the peak intensity of anatase was the same for all samples, suggesting that the thickness of anatase and the orientation relationships were the same. This implies that only their morphology could affect the apatite forming ability.

Fig. 7 present the cell adhesion and morphology on hydrogen peroxide treated titanium samples at 100 °C and different concentrations of chlorine.

The number of attached cells on the HHT-0-100, HHT-3-100, HHT-6-100, and HHT-12-100 samples are about 2400 ± 18, 1925 ± 27, 1724 ± 21 and 1438 ± 19 cells/mm^2, respectively. It is evident that more L-929 cells were attached to the HHT-0-100 sample, as compared to others. By increasing the chlorine concentration of hydrogen peroxide, fewer cells were attached on the surface of the sample. This could be because of the toxic effect of the residue chlorine at the surface and also, the surface morphology of the treated samples. According

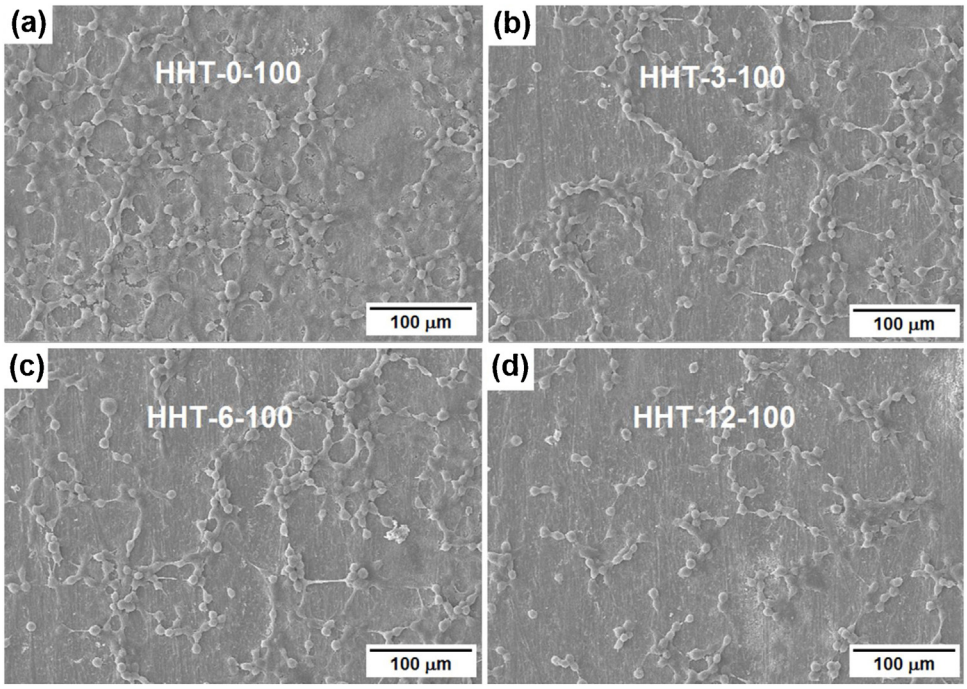

Fig. 7 – The L-929 cell adhesion on: (a) HHT-0-100, (b) HHT-3-100, (c) HHT-6-100, and (d) HHT-12-100 samples.

to Figs. 5–7, it is evident that chlorine would result in less bio-functionalization (wettability, apatite forming ability and cell adhesion) of hydrogen peroxide treated titanium samples at 100 °C. However, anatase and/or rutile could improve the osteogenic activity of titanium implant [22], and the hydrogen peroxide treatment would result in anatase formation on the titanium surface. Of course, other studies have shown that hydrogen peroxide could improve the wettability and blood and cell compatibility of the NiTi shape memory alloy [23]. So, it can be said that choosing the appropriate condition of hydrogen peroxide treatment could result in the better bio-functionalization of titanium and titanium alloys for implantation.

4. Conclusion

In this study, a rigid titanium implant material, was surface-treated using hydrogen peroxide at different temperatures and in the presence of different concentrations of the chloride ion. The results showed that the effect of hydrogen peroxide was different at different temperatures. At the lower temperatures of treatment, hydrogen peroxide acted as a corrosive medium, corroding the titania layer, while further post-heat treatment resulted in rutile formation on the surface. The treatment at higher temperatures, resulted in a relatively crack-free titania layer and further post-heat treatment led to the anatase nanowire formation at the surface. Although all samples treated at 100 °C showed a superhydrophilic behavior and a good apatite forming ability, the morphology of anatase, hydrophilicity, apatite forming ability, and the cell adhesion ability of the titanium implant material were affected by the chloride ion concentration of the hydrogen peroxide solution.

Conflicts of interest

The author declares no conflicts of interest.

Acknowledgments

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