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Low-temperature fabrication of Ag-doped HA coating on NiTi

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Abstract

NiTi is widely used as bone plates for fixation in bone fracture surgery. For such implant applications the bone plates are commonly coated with hydroxyapatite (HA) to facilitate osseointegration, and doped with silver (Ag) to impart an antibacterial function. In the present study these were achieved via a low-temperature route so as not to disturb the built-in thermomechanical properties of NiTi. An Ag-doped Ca-P coating was first formed on NiTi using AC electrodeposition in an electrolyte containing Ag, Ca, and P ions. The coated samples were subsequently hydrothermally treated at 180 °C for 24 hours to form HA. The coated samples were immersed in Kokubo's simulated body fluid (SBF) and release of Ag ions in regularly refreshed SBF was measured at regular intervals up to 32 days. It was found that the Ag ion release rate reached a steady value after two weeks, and the Ag ion concentration in the SBF stayed at around 1 μM, a value which is effectively antibacterial and yet non-cytotoxic according to the literature.

Keywords: Electrodeposition; Ag-doped HA coating; Ag ion release; Metals and alloys; Biomaterials; NiTi

1. Introduction

Metallic bone plates are widely used in bone fracture surgery for internal fixation. Implant loosening due to poor osseointegration and bacterial infection are two major causes of implant failure. Thus to increase the success rate of implantation, various methods have been developed to fabricate Ag-doped HA

coating on bone plates aiming at enhancing osseointegration and imparting an antibacterial function. These include microwave processing [1], sputtering [2], sol-gel method [3] and plasma spraying [4]. NiTi, by virtue of its shape memory effect or super-elastic properties, is a popular bone plate material, but it is susceptible to undesirable disturbance of the built-in thermomechanical properties when it is subjected to a processing temperature of 300 °C or above. This special requirement motivates the authors to attempt a low-temperature method for fabricating Ag-doped HA coating on NiTi. The incorporation of different types of nanoparticles in HA coatings or scaffolds has also been reported in a series of recent papers by Xie et al. [5-7]. While the osseointegrative property of HA [8-9] and the antibacterial effect of Ag [10-11] are well documented, the present study focuses on fabricating a Ag-doped HA coating via a new low-temperature route comprising electrodeposition followed by hydrothermal treatment. The results of this new method show that the Ag-doped HA coating fabricated would release Ag ions steadily at a safe and effective level over a long period.

2. Material and methods

NiTi samples of 13 mm x 13 mm x 5 mm were used as electrodes in AC electrodeposition as detailed in [12]. The electrolyte was composed of 0.2 M calcium acetate and 0.04 M sodium β-glycerophosphate pentahydrate, with $AgNO_3$ concentration varying from 2 mM to 2 μM, and the current was 3 A, for 10 min. The samples prepared were designated as "2 mM sample", etc. according to the [$AgNO_3$] used.

To induce HA formation, and to improve the compactness and adhesion of the coating, the samples were subsequently hydrothermally treated in an autoclave containing CaP solution (0.2 M calcium acetate and 0.04 M sodium β-glycerophosphate pentahydrate) at 180 °C for 24 hours. The samples were then

suspended vertically and immersed in c-SBF (conventional simulated body fluid proposed by Kokubo and Takadama [13]), and kept at 37 °C, pH = 7.4, in polypropylene bottles. The ratio of volume to exposed area was about 0.1 mL/mm^2. The c-SBF was collected and refreshed every two days to simulate physiological fluid exchange [14]. The total immersion period lasted for 32 days as it has been pointed out that acute orthopedic-device-related infection (ORDI) may occur in the first month after surgery [15]. To determine the concentration of Ag ions in the SBF, ICP-MS (Perkin Elmer DRC II) was used. In addition, the coatings at different stages were characterized using SEM (Tescan VEGA3), EDS (Oxford Instruments X-Max^N 50) and XRD (Rigaku SmartLab).

3. Results and Discussion

3.1 Characterization

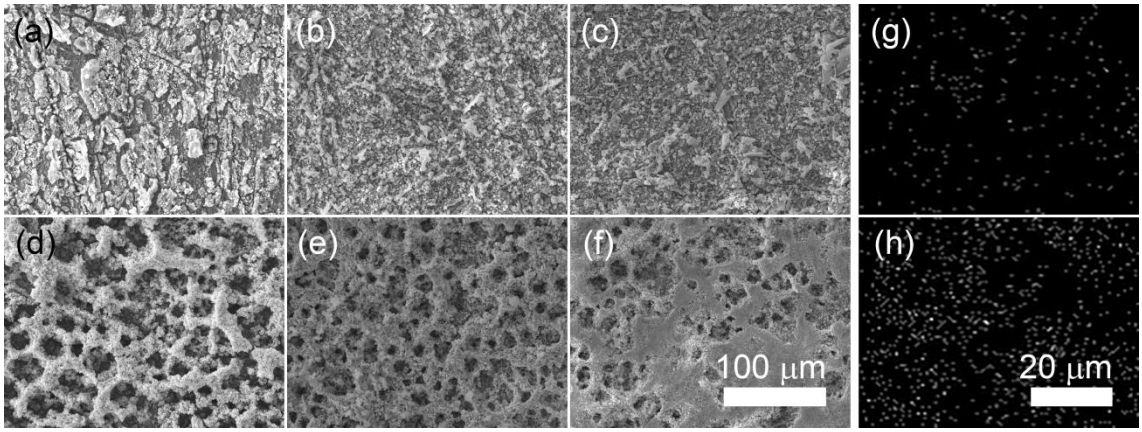

Fig. 1 SEM micrograph: (a) as-deposited, (b) HT-treated and (c) post-immersion, of the 200 µM sample. (d-f) are corresponding micrographs of the 2 mM sample. (g) and (h): EDS mapping of Ag of corresponding HT samples

As observed in the SEM micrograph in Fig. 1(a) and (d), AC electrodeposition created a rough coating on NiTi. In comparison the 2 mM samples were more porous than the 200 µM, probably due to the presence of more conducting particles arising from a high concentration of Ag. The 2 µM and 20 µM samples shared similar features as the 200 µM sample and are not shown here. In all cases, the

as-deposited coatings were loosely adhered to the substrate and could be easily removed by scratching. On the other hand, coating was strongly adhered to substrate after hydrothermal treatment, possibly due to the high hydrostatic pressure during hydrothermal treatment and inter-diffusion between the coating and the substrate. The EDS mappings of Ag in Fig. 1 (g) and (h) show uniform distribution of Ag particles.

[Ag] in starting electrolyte	**Ag:Ca (as-deposited)**	**Ag:Ca (HT-treated)**	**Ag:Ca (after immersion)**	**Ca:P (HT-treated)**	**Ca:P (after immersion)**
2 mM	10:1	1:1	0.41:1	1:1.69	1:1.63
200 μM	0.99:1	0.20:1	0.19:1	1:1.57	1:1.65
20 μM	0.06:1	~ 0:1	~0:1	1:1.57	1:1.52
2 μM	~0:1	~0:1	~0:1	1:1.65	1:1.58

Table 1. Compositions of coatings at different stages as estimated by EDS

Table 1 shows that Ag was incorporated into the HA coating during the electrodeposition process. When [Ag] in the electrolyte decreased, the doped Ag content in the coating also decreased and became negligible at [Ag] = 2 μM or 20μM. The values of Ag:Ca in the coating decreased after hydrothermal treatment, and after the 32-day immersion test, the samples showed a further decrease in Ag:Ca, indicating release of Ag ions from the coating to the SBF during the test. It is interesting to note that there is only little decrease in Ag:Ca of the 200 μM sample after the immersion test. This indicates that the Ag reservoir in the coating could sustain steady supply of Ag ions for a longer period. In addition, no Ni or Ti ions were detected in the SBF after the immersion test, indicating a good barrier coating on the substrate. The values of Ca:P of all the coatings were quite near to 1.67 after hydrothermal treatment and after the immersion test. From the XRD patterns in Fig. 2, the existence of Ag peaks in the coatings of the 200 μM and 2 mM samples is consistent with the EDS results.

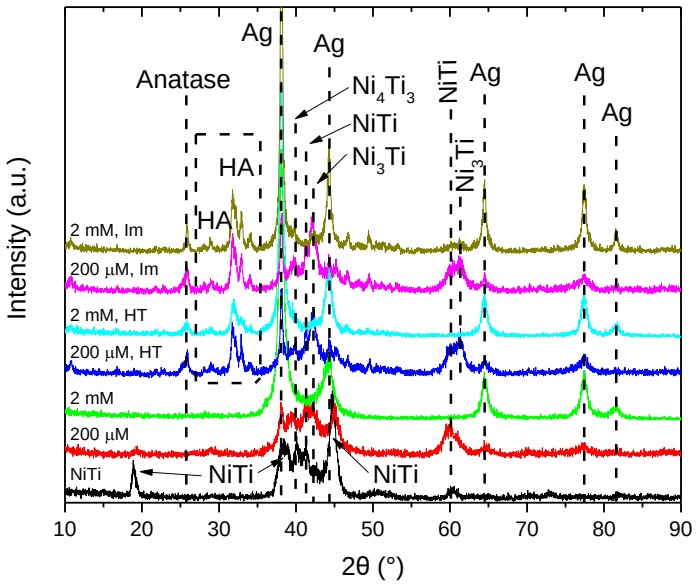

Fig. 2. XRD patterns of the as-deposited, HT-treated (HT) and post-immersion test (Im) samples prepared using solution with [Ag] = 200 μM and 2 mM.

On the other hand, the appearance of HA peaks after hydrothermal treatment was due to the formation of HA crystals in the coating. Slight increase in intensity of HA peaks after immersion is attributed to the growth of HA induced by Kokubo's SBF. The coating thickness of all samples after hydrothermal treatment was roughly the same, being ~150 nm from cross-sectional micrograph (not shown).

3.2 Ag ion release

For ideal antibacterial effect of the coating, it should steadily release Ag ions to its vicinity over a sufficiently long period. Usually the first month after surgery is the most critical for successful implantation [15]. Hence a quasi-long-term study of Ag ion release in 32 days of immersion was carried out in the present study. From Fig. 3, the values of [Ag] in the collected SBF for the 2 μM and 20 μM samples were below the 5-ppb detection limit. On the other hand, the 2 mM sample yielded a Ag

concentration of more than 7 μM (or a corresponding release rate of ~35 x 10^{-9} mol/cm^2/day) in the whole immersion period, which exceeded the cytotoxicity limit according to Ning et al. [16]. The concentration of Ag ion detected in the SBF from the 200 μM sample was high initially, but then fell rapidly to a safe level of around 1 μM within the first 2 weeks. Afterwards it stayed steady at 1 μM (or a corresponding release rate of ~5 x 10^{-9} mol/cm^2/day), a value which is effectively antibacterial against S. aureus and E. coli and yet not cytotoxic to fibroblast cells L929 [16]. As a comparison, the coatings fabricated by coprecipitation still released [Ag] 3 times higher than the cytotoxicity limit at the end of the 2-week immersion test [17], while coatings doped with Ag^+ by ion-exchange released Ag^+ much higher than the cytotoxicity limit even after one week [18].

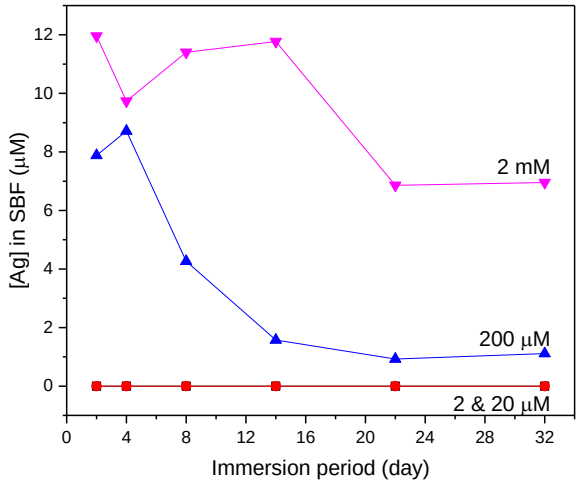

Fig. 3. [Ag] in immersion SBF due to Ag ion release from Ag-doped HA coating.

In addition, no Ti or Ni ions were detected in the SBF in the present study, suggesting a good barrier coating on NiTi.

In general, it is well known that the Ag ion release rate from a Ag-containing coating is not constant

over the initial period and would reach a steady value after a certain period. It is this steady value that is of long-term importance for implant applications. The important issue is the attainment of a steady value in the correct range, as is in the present case. The initial fluctuation can be removed by a simple pre-treatment, if required, by immersion in SBF for some time to attain the steady value.

4. Conclusions

To create an antibacterial and bioactive surface on NiTi implant, a Ag-doped HA coating was fabricated via AC electrodeposition followed by hydrothermal treatment. The following concluding remarks can be drawn:

1. Compared with other methods of fabricating Ag-doped HA coating on metallic implants, the present method involves a much lower temperature (<200 °C). This is particularly important for NiTi as its built-in thermomechanical properties would be unfavorably disturbed at processing temperatures >300 °C.

2. With $AgNO_3$ at a concentration of 200 μM in the starting electrolyte, steady Ag ion release can be achieved over a period of at least four weeks during immersion of the coated samples in SBF.

3. The Ag ion concentration in regularly refreshed SBF in the immersion test is around 1 μM. According to literature, this concentration is effectively antibacterial against S. aureus and E. coli and yet not cytotoxic on fibroblast cells L929.

4. During the immersion period no Ni or Ti ions were detected in the SBF, indicating a protective barrier HA coating on NiTi.

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