Immobilized Heparin onto TiNi Shape Memory Alloy Modified with Acrylamide by UV-Induced Grafting

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SiC:H organic-like thin films are deposited on Ti50Ni50 shape memory alloy by DC-pulsed plasma enhanced chemical vapor deposition (PECVD) in the gas mixture of Hexamethyldisilazane (HMDSN) and Ar at room temperature. The organic-like thin films containing peroxides or free radicals can be successfully grafted with hydrophilic polymer acrylamide (AAm) by UV-induced grafting polymerization. After grafting, a new dense organic and slippery surface with low friction coefficient is obtained. Heparin is finally immobilized onto grafted-AAm thin films to take TiNi SMA into the anti-thrombin biomaterials. [doi:10.2320/matertrans.48.348]

Keywords: TiNi shape memory alloy, Hexamethyldisilazane (HMDSN), DC-Pulsed plasma enhanced chemical vapor deposition (PECVD), Acrylamide (AAm), Heparin

1. Introduction

Equiatomic TiNi shape memory alloy (SMA) exhibiting excellent shape memory effect (SME), superelasticity and biocompatibility1) has drawn a lot of attention for decades as a functional material in a variety of industrial and medical applications. It has a long history of using TiNi SMA as a biomaterial in applications such as the intracoronary stent,2) the ligaments’ replacement,3) the shape memory microvalve4) etc. The biocompatibility of metal implants is generally evaluated by the reaction between metal and the surrounding tissue. The intensity of the damage caused by metallosis is proportional to the quantity of toxic metallic ions produced by corrosion. In TiNi SMA, titanium is not detrimental among the essential trace elements,5) while nickel proves to exhibit high carcinogenic and toxic potencies in vivo regardless the fact that Ni is an essential element to the human body.6)

Furthermore, when a foreign material is exposed to blood, plasma proteins are adsorbed onto the material surfaces, followed by the activation of clotting factors or the adhesion/activation of platelets, and finally carried out formation of fibrin networks, i.e., thrombus formation. A lot of research has been performed using various hypotheses in order to develop highly antithrombogenic materials. Heparin, a well-known anticoagulant, has been the most frequently used as an immobilizing biomolecule for attaining the blood compatibility of materials.7–10 It is considered as one of the most suitable biomolecules for the inhibition of thrombus formation in the initial stage of blood-material contact. Besides, a number of investigations have been carried out on heparin immobilization, showing the effectiveness of achieving antithrombogenicity.

In this study, the coatings of plasma polymerized hexamethyldisilazane (PPHMDSN) are employed to improve the corrosion of TiNi SMA and also to prevent the Ni ions releasing from TiNi alloy. However, the relatively high surface hydrophobicity of the PPHMDSN thin films, which results in the adsorption of significant amounts of protein, constrains their use in biomedical applications. In order to overcome this restriction, organic-like PPHMDSN thin films containing peroxides or free radicals are subsequently grafted with hydrophilic polymer acrylic amide (AAm) by UV-induced grafting polymerization. Heparin is immobilized onto grafted-AAm thin films to take TiNi SMA as the anti-thrombin biomaterial. The characteristics of immobilized heparin onto TiNi SMA modified with AAm by UV-induced grafting are also discussed.

2. Experimental Procedure

2.1 Plasma polymerized HMDSN on TiNi alloy

The Ti50Ni50 SMA was prepared from titanium (99.8 mass%) and nickel (99.98 mass%) by using a vacuum/argon tungsten arc furnace. The casting ingot was hot-rolled into a rolled sheet of Ti50Ni50 (plate) was placed in the DC-pulsed PECVD equipment and connected to a bipolar pulsed power source. The amplitudes of positive and negative pulses were 600 V and −800 V, respectively. All plasma deposition was carried out under the given bipolar pulsed source for 10 min. The duty cycle was around 0.83. Frequency of the pulsed wave was about 1.38 kHz. During deposition, the pressure was maintained at 250 mtorr. The film formed on the cathode has a highly cross-linked density.

2.2 Graft polymerization

The surface of plasma-deposited film contained activated species which can react with the oxygen and moisture in air to form peroxides. Peroxides could further provide active sites for surface graft polymerization induced by UV light with acrylamide (AAm, C3H5CONH2, Wako Pure Chemical Industry, Japan.) monomers. The aqueous AAm monomer solution was prepared and mixed with 0.01 g/L riboflavin to initiate graft polymerization under UV irradiation (λmax = 450 nm) to form a highly cross-linked density graft copolymer film.
remove oxygen.\textsuperscript{12} TiNi alloy with PPHMDSN thin films were immersed into the monomeric solution and irradiated with UV light of 1000 W (wavelength: 365 nm, Henchman Co. Inc., Taiwan) for 30 min to initiate the grafting polymerization. The formed homopolymer of PAAm was removed from the grafted film by washing in distilled water for 24 h under continuous stirring.

2.3 Immobilization of heparin
All solutes, which include 1000 mg heparin (sodium salt, 170 USP units mg\textsuperscript{-1}, Sigma Chem. Co., USA), NHS (50 mg/50 mL N-Hydroxy-succinimide, C\textsubscript{4}H\textsubscript{2}Chem. Co., USA) and buffer solution-MES sodium salt (0.1 M, pH ¼ 5.5–6.7, Sigma Chem. Co., USA) were sequentially dissolved in 5 mass% distilled water for 48 h under continuous stirring.

3. Results and Discussion
3.1 FTIR
The thickness of SiC:H organic-like (PPHMDSN) thin film deposited on TiNi alloy by DC-pulsed PECVD of Hexamethyldisilazane (HMDSN) and Ar gas mixtures for 10 min is about 351.5 nm. Figure 1(a) shows the infrared (IR) spectra of the grafted PAAm after the grafting polymerization in different concentration of AAm monomer solution. The grafted film on the plasma-deposited PPHMDSN layer shows the carbonyl band (C=O) at about 1600 cm\textsuperscript{-1}, then -CONH\textsubscript{2} bands at 3050–3510 cm\textsuperscript{-1}, the O–H bands at 3200–3600 cm\textsuperscript{-1} and the N–H bands at 3300–3500 cm\textsuperscript{-1}. The three bonds, -CONH\textsubscript{2}, O–H and N–H, overlap and form the intense peak around 3000–3600 cm\textsuperscript{-1} which do not appear in the IR spectra of PPHMDSN thin films. It is reasonable that the higher the concentration of the monomer solution will lead to the more grafting on the surface, and therefore the stronger peak of the amide group on IR spectra can be observed in Figs. 1(b)–(d).

3.2 Wettability
The wettability can be evaluated from the water contact angle of specimens, as illustrated in Table 2. The material hydrophilicity is determined by its chemical structure. The stronger the polarity of the functional groups, the better the affinity with water. The water contact angle of as-polished TiNi alloy is 42°. After PPHMDSN deposition, the water contact angle will raise from 42° to 87° because the PPHMDSN film consists of more non-polar groups as methyl and methylene.\textsuperscript{16} However, after the grafting polymerization of hydrophilic monomer AAm, the water contact angle of the grafted films decreases significantly to a level lower than 60°. The higher the concentration of the monomer solution is, the smaller the water contact angle it has. While the concentration of the AAm monomer solution is 15 mass%, the water contact angle decreases to 33° which is even lower than TiNi substrate.

The other index for evaluating the slippery surface is the wet friction test. Samples with different applied loads were moved onto the wet glass. The lateral force and displacement are measured, as typically shown in Fig. 2. The relative wet friction coefficient listed in Table 3 can be determined from the slope of the linear relationship between the maximum lateral force and the applied load, as the example of TiNi substrate shown in Fig. 2(b). The relative wet friction coefficient of TiNi alloy is about 0.2217. After deposition of PPHMDSN thin film, the surface becomes more hydro-

![Fig. 1 The IR spectra of (a) the PPHMDSN thin film, and (b)–(d) the grafted PAAm from (a) with different concentration (b) 5 mass%, (c) 10 mass% and (d) 15 mass% of the AAm monomer solution.](image-url)

<table>
<thead>
<tr>
<th>Chemical Bonds</th>
<th>Absorption Peak/cm\textsuperscript{-1}</th>
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<tbody>
<tr>
<td>Si–C</td>
<td>790</td>
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<tr>
<td>Si–(CH\textsubscript{3})\textsubscript{2}</td>
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<td>Si–O</td>
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<tr>
<td>N–H</td>
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</table>

Table 1 The chemical bonds and their related absorption peaks of PPHMDSN thin films shown in Fig. 1.
phobic, leading to the increase of relative wet friction coefficient (0.2539). However, after the grafting polymerization of hydrophilic AAm monomer, the relative wet friction coefficient declines to less than 0.2.

### 3.3 Surface morphology

Figure 3 shows the atomic force microscope (AFM) 3D image of various AAm grafting on PPHMDSN-deposited TiNi specimens. The grafting initiates at the peroxides or at the points activated by the plasma. The IR spectra indicate that the amide characteristic absorption peaks are low when the concentration of the AAm solution is 5 mass%. The surface roughness (root mean square) raises from 3.2 nm of PPHMDSN thin film to 3.702 nm of that with grafting in 5 mass% AAm monomer solution. It suggests that the grafting is confined to small regions. As the concentration becomes denser, the grafted region is getting larger. Gradually, it turns into a new organic thin film layer and the surface roughness reduces substantially to 1.2–1.3 nm, as shown in Figs. 3(a) and 3(b).

Figure 4 shows the SEM image of the PPHMDSN thin films with grafting in 10 mass% AAm monomer solution. According to AFM, it suggests that the surface roughness is too low to discern any obvious contrast even in the high magnification. Nevertheless, Figure 4(a) shows the SEM image of the sample center in which PPHMDSN thin film is densely covered with a new organic PAAm thin layer with fine crack structure. Figure 4(b) shows the SEM image of the
sample edge in which there is a boundary between the PPHMDSN thin film and the new organic PAAm thin layer.

### 3.4 Immobilization of heparin

Figure 5 shows the XPS spectra of the immobilization of heparin on PAAm grafted substrate after turbulent washing. The binding of C1s is located at 284.3 eV, O1s is located at 531.4 eV, N1s is located at 399.35 eV, Si2p is located at 103 eV, and S2p is located at 162.2 eV. Compared to the element components before immobilization of heparin, the presence of element S can be used to prove that heparin is covalently immobilized on TiNi SMA.

### 4. Conclusions

SiC:H organic-like thin films are deposited on TiNi SMA by DC-pulsed PECVD of HMDSN and Ar gas mixtures at room temperature. The organic-like thin films containing peroxides or free radicals can be subsequently grafted with hydrophilic polymer AAm by UV-induced grafting polymerization. Heparin is immobilized onto grafted-AAm thin films to take TiNi SMA into the anti-thrombin biomaterials. The AAm grafting can be verified from the presence of amide group according to the IR spectra. After grafting polymerization of AAm, a new dense organic thin layer is formed. The higher the concentration of hydrophilic AAm monomer solution is, the smaller the water contact angle it has. Moreover, the surface roughness reduces substantially when the concentration is higher than 10 mass%. The relative wet friction coefficient declines to as low as 0.2. These slippery properties are beneficial to the biomedical applications of TiNi SMAs.

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### REFERENCES


