Surface Modification of Titanium Based Biomaterials by Ion Beam

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Abstract Ion beam enhanced deposition (IBED) was adopted to synthesize biocompatible titanium oxide film. Structure characteristics of titanium oxide film were investigated by RBS, AES and XRD. The blood compatibility of the titanium oxide film was studied by measurements of blood clotting time and platelet adhesion. The results show that the anticoagulation property of titanium oxide film is improved significantly. The mechanism of anticoagulation of the titanium oxide film was discussed.

Key words IBED, titanium oxide film, blood compatibility, clotting time, platelet adhesion

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1. Introduction

The relationship between surface states and biocompatibility of materials is of topic concern in the development of a biomaterial. Low temperature isotropic pyrolytic carbon (LTI-carbon) and titanium alloys are usually used for fabrication of artificial heart valves because of their combination of blood compatibility and high resistance to degradation, wear and fatigue. The main problem of mechanical heart valves is their thromboginicity. Life-time anticoagulation therapy is necessary to minimize the risk of thromboembolic complications[1]. It has been found that when a titanium oxide layer of rutile structure was formed on titanium matrix, the blood compatibility was obviously improved, and better than that of LTI-carbon[2]. This paper presents an investigation result of the blood compatibility of titanium oxide film synthesized by ion beam enhanced deposition.

2. Experimental Procedure

2.1 IBED synthesis of titanium oxide film

The titanium oxide film was synthesized by using an EATON Z-200 ion beam mixing and deposition system. Concurrent electron beam evaporation of titanium and bombardment with Xe^+ ions were carried out in an O_2 environment. The pressure of O_2 during processing was $6\sim13\times10^{-4}$Pa. The acceleration voltage of Xe^+ ions was 20~40 keV with the current density of 7.3~40 $\mu A/cm^2$. The deposition rate of titanium atoms was varied in the range of 1~10 angstrom/s. The substrate temperature was controlled to be lower than 180°C by using water cooling.

2.2 Measurements of structure and composition of the film

The composition of titanium oxide film was measured by AES and RBS. Valence state of the elements was detected by XPS. The XRD was used to identify the structure of the films. And, the resistivity was measured by four probe system.

2.3 Blood compatibility experiment

2.3.1 Clotting time measurement

The kinetic method to measure thromboresistant property was used. Blood was taken from the heart of rabbit by using a plastic syringe, and 0.1 ml blood was immediately dropped onto a testing specimen. After a predetermined time, the specimen was transferred into a beaker containing of 50 ml distilled water. The red blood cells which had not been trapped in thrombus were hemolyzed, and the free hemoglobin were distributed dispersively in the water. The concentration of the free hemoglobin in the water was colorimetrically measured as optic density at 540 nm wave length with a spectrometer. The optic density of the solution versus time was plotted. Beside IBED synthesized titanium oxide films, the clotting properties of low temperature isotropic pyrolytic (LTI) carbon, glass and uncoated titanium alloy were also investigated for comparison.

2.3.2 Platelet adhesion

The number and morphology of adherent platelet were measured as parameter for surface thrombogenicity studies.

Blood was drawn by venous puncture. Platelet-rich plasma was dropped onto surface of specimen, and incubated in 37 °C for 1.0 hr.. After rinsing, fixing, critical point drying, the specimens were coated with gold-palladium, and observed with optic microscopy and scanning electron microscopy. 20 fields of vision were investigated to obtain the morphology and statistic results of absorbed Platelets.

3. Experimental Results

3.1 Structure and composition of IBED titanium oxide film

AES and XRD analysis show that the O/Ti ratio of the titanium oxide film is increased from 0.45:0.55 to 2:1 with increasing of Po_2/V_{Ti} (Fig.1). And the structure of the prepared film changed from crystalline to amorphous (Fig.2). From XPS measurement, it could be concluded that the oxide film was composed of TiO_2 .

3.2 Blood compatibility

3.2.1 Clotting time profiles

Fig.3 shows the blood profiles on the tested materials. The optic density (at 540 nm wave length) of the hemolyzed hemoglobin solution changed with time. The higher the optic density in definite time is, the better the thromboresistance is. Conventionally, the time at which the optic density decreased to 0.1 is regarded as clotting time. The experiments showed that the clotting time of IBED synthesized films is obviously longer than that of LTI-carbon and other reference materials. Optimal clotting time could be obtained when the experimental parameters were controlled precisely (Fig.4).

3.2.2 Platelet adhesion

Fig.5(a) is the statistic results of platelet adhered to the surface of testing materials. The adherent Platelet on IBED coated titanium oxide layer is much less than that of on the LTI-carbon surface and uncoated titanium alloy.

Fig.5(b) is the statistic results of aggregate tendency of platelet on the surface of testing material. It could be hardly found that the platelet in aggregate state on the surface of IBED-TiO_2 film synthesized on the best condition. The aggregation of platelet on LTI-carbon surface was in certain degree. The more serious aggregation accrued on untreated titanium alloy. In the experiments, no significant evidence of deformed platelets such as pseudopodium were observed for all materials.

4. Discussion

The formation of thrombosis on an artificial material is correlative with charge transfer from the inactive state of the protein (e.g., fibrinogen) to the surface of the material. During the process, fibrinogen is oxidized and transforms to fibrinmonomer, then cross-links to the irreversible thrombus (Fig.6). Fibrinogen has an electronic structure similar to a semiconductor and has a 1.8 eV band gap[3]. Certain electronic structure states on the material surface could possibly inhibit the transfer of the charge carrier. Fig.7 is the schematic model of the energy band structure of a metal-oxide layer-electrolyte system. For TiO_2, the energy band gap is 3.2 eV[4]. If the oxide layer on the titanium surface has the semiconductor property, the oxidization process of fibrinogen will be inhibited, or at least, delayed. Because the conduct band and valence band of fibrinogen fall into the energy gap of rutile, if the defect density in a rutile is low and location states of the band gap as well as the cavity density could be kept at a low level, the possibility of electrons transferring from fibrinogen to the solid surface would be limited. Meanwhile, there is a big difference in work functions between titanium and titanium oxide. Many electrons would transfer from titanium to the oxide layer and a space charge region would be formed. The electron density in the conduct band of the oxide layer will be increased and the surface will be a negative charge state. This would result in a favorable electrochemical equilibrium condition and inhibit thrombosis.

The effect of thrombosis of titanium oxide film also depends upon its crystal structure, thickness and energy level, as well as density of impurities and defects, surface states, etc.. Ion beam enhanced deposition provide an useful technique for control of composition and structure of titanium oxide film.

5. Conclusion

Experimental investigation showed that the blood compatibility of biomaterials could be dramatically improved by forming an titanium oxide layer on the surface. Ion beam enhanced deposition is promising to obtain thromboresistant materials better than LTI-carbon.

References

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Captions

Fig.1 Composition of titanium oxide film measured by AES as a function of experimental parameters

Fig.2 X-ray diffraction pattern of titanium oxide films

Fig.3 Blood clotting profiles on the various material surface

Fig.4 Blood clotting time versus the experimental parameters

Fig.5 Platelet adhesion

Fig.6 Formation of thrombosis on an artificial material

Fig.7 Schematic model of the energy band structure of titanium/oxide layer/fibrinogen solution system

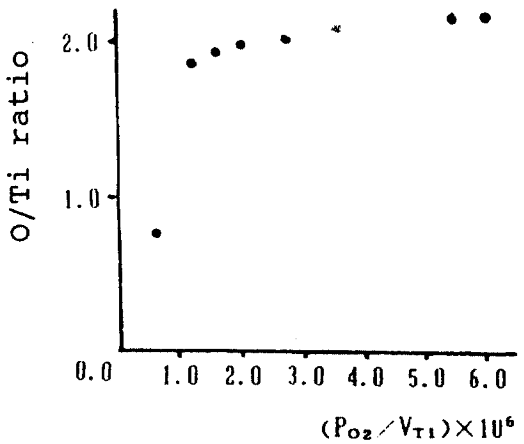
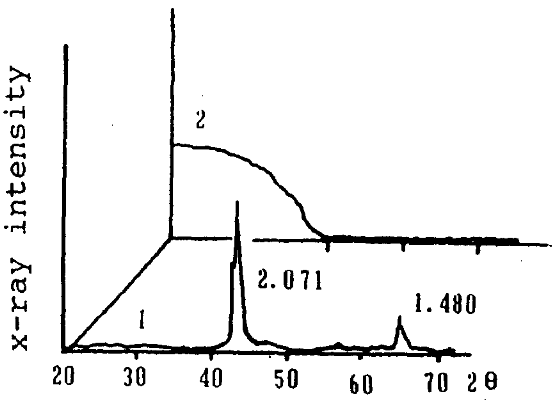


Fig. 1 Composition of titanium oxide film measured by AES as a function of experimental parameters

AES analysis shows that O/Ti ratio of titanium oxide film is increased from 0.45:0.55 to 2:1 with increasing of Po2/V



1. $P_{O_2}/V_{Ti}=0.65$ 2. $P_{O_2}/V_{Ti}=2.74$

Fig.2 X-ray diffraction pattern of titanium oxide films

XRD measurement revealed that the structure of prepared film Changes from crystalline to amorphous

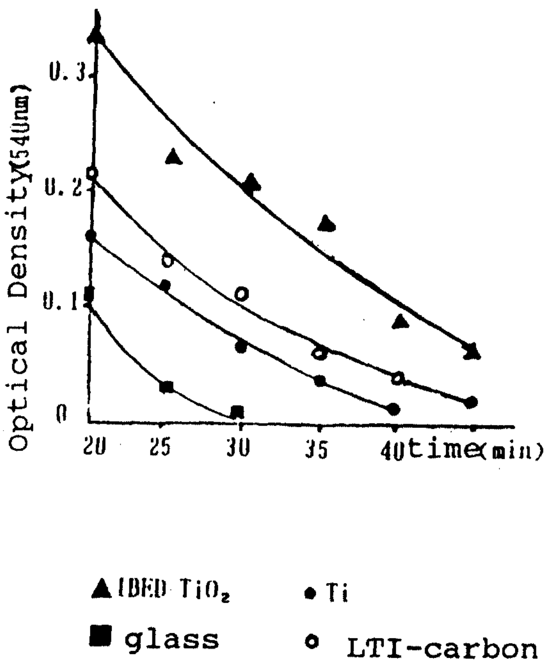


Fig.3 Blood clotting profiles on the various material surface

The optical density of the hemolyzed hemoglobin solution changed with time

clotting time: the optic density decreased to 0.1

It shows that the clotting time of IBED TiO2 is longer obviously than that of LTI-carbon and other reference materials.

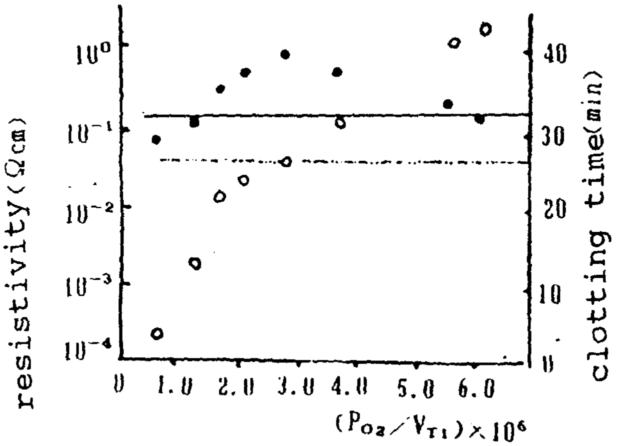


Fig.4 Blood clotting time versus the experimental parameters

optimal clotting time could be obtained when the experimental parameters were controlled precisely

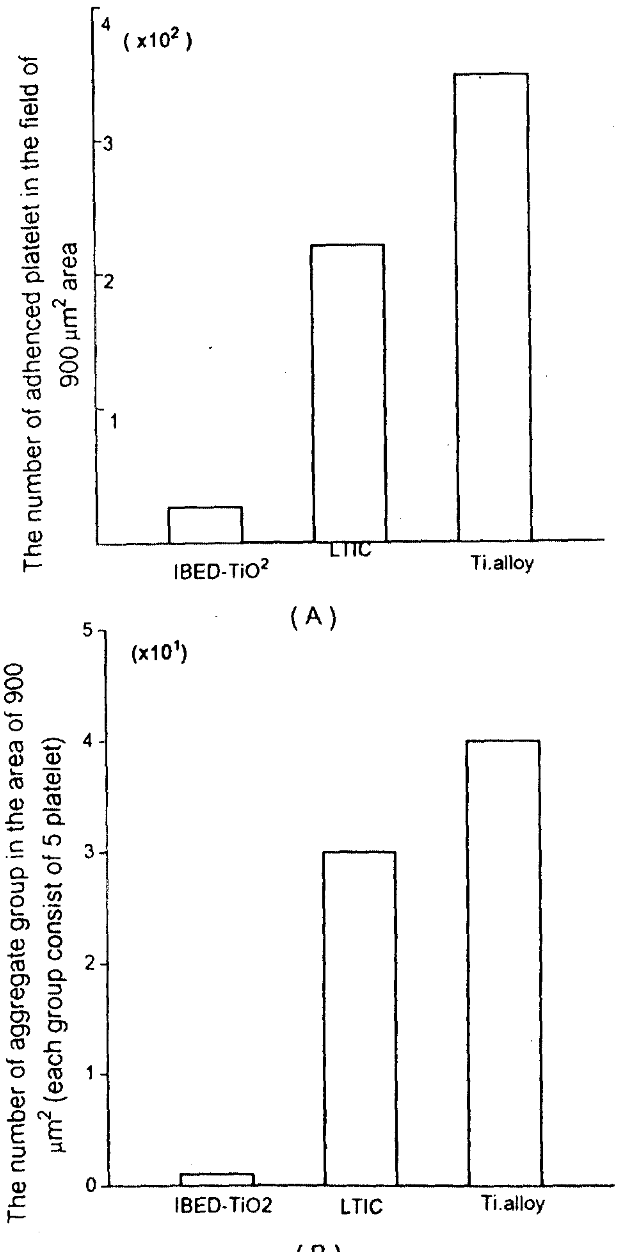


Fig.5 Platelet adhesion

the adherent Platelet on IBED coated titanium oxide layer is much less than that of on the LTI-carbon surface and uncoated Ti alloy.

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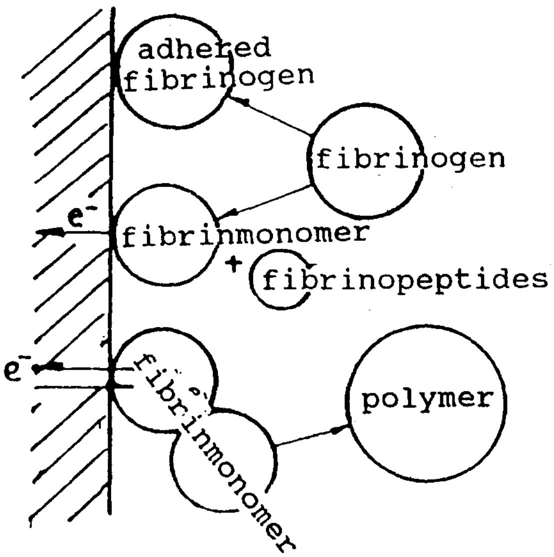

Fig.6 Formation of thrombosis on an artificial material

The formation of thrombosis on an artificial material is correlative with charge transfer from the fibrinogen to the surface of the materials. During the processing, fibrinogen is oxidized and transforms to fibrinmonomer,then cross-likes to the irreversible thrombus

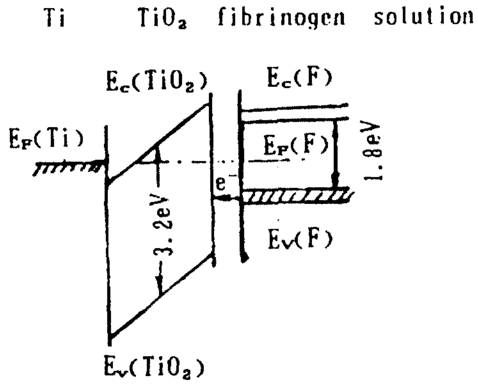

Fig.7 Schematic model of the energy band structure of titanium/oxide layer/fibrinogen solution

If the oxide layer on the Ti surface has the semiconductor property, the oxidization of fibrinogen will be inhibited, or at least, delayed.

work function: Ti > TiO2
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