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Electrochemical Impedance Spectroscopy Studies of Porous Titanium Foams Intended for Orthopaedic Applications

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Since the mid-1980s, many porous biomaterials have been developed for hard and soft tissue ingrowth while porous implants are becoming increasingly important in orthopaedics and dentistry. The interest mainly comes from the fact that interconnected porosity allows tissue ingrowth and integration. Porous titanium has been used extensively for that purpose in orthopaedics. A new process [1] has been developed recently to produce porous materials having structure and properties similar to those of cancellous bones, see Fig. 1. The main purpose of the present paper is to study the TiO₂ layers of the foams by Electrochemical Impedance Spectroscopy (EIS).

Fig. 1. SEM Ti foam micrograph

Modifying the initial powder mixture and the thermal treatment conditions produced materials having different microstructures (A, B1, B2 and B3) [2]. Electrochemistry was used to: i) determine the surface area by EIS, ii) find the corrosion current density (*j*₀) (simulated body fluid, 37°C and after 18 h at *E*_{corr} or 144 h for B2A and B3A) and the penetration rates (*PR*) and iii) study the TiO₂ layers by EIS at *E*_{corr}. For all the different foams, the best EIS fittings were obtained using the equivalent circuit shown in Fig. 2. *Q*_{ox1} and *R*_{ox1} are related to the outer TiO₂ layer while *Q*_{ox2} and *R*_{ox2} are related to the inner one. *Q*_p and *R*_p are related to the porous nature of the foam. Figures 3 and 4 show the corresponding experimental and simulation data for foam A, B2 and B2A.

Fig. 2. Eq. circuit used for EIS modeling of the Ti foams.

Fig. 3. Nyquist diagram for Foam A. Experimental data (○) and EIS modeling data using EC2 (—).

Fig. 4. Bode diagrams for Foams B2 (○) and B2A (△), experimental data and EIS modeling data using EC2 (—).

The thickness (*l*) of the inner dense TiO₂ layer formed on flat polished titanium can be calculated using the capacitor parallel-plate equation (1) which was simplified to equation (2) since the depression angle α_{ox2} was close to unit (0.995 +/- 0.010). The constant phase elements (*Q*_{ox2}) for the different foams vs. the corresponding penetration rates are shown in Fig. 5.

$$l = \frac{\epsilon_{ox2} \epsilon_0 A}{C_{ox2}} \tag{1}$$

$$l = \frac{8.9 \times 10^{-12} \epsilon_{ox2}}{Q_{ox2}} \tag{2}$$

Fig. 5. Constant phase element of the inner TiO₂ layer obtained by EIS versus penetration rate for solid titanium and the different Ti foams.

Since *Q*_{ox2} is inversely proportional to the thickness of the inner dense TiO₂ layer, the corrosion resistance of the titanium foam increases with the thickness of its oxide layer.

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[1] Lefebvre L-P, Thomas Y. US Patent 6660224
[2] Gauthier M, Menini R, Bureau MN, So SKV, Dion MJ and Lefebvre LP. Proceedings of the ASM Materials & Processes for Medical Devices Conference. p382. 8-10 Sept., Anaheim CA, 2003.