Investigation of the interaction between biocorrosion and biofilm development based on the pH profile

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We propose a combined model investigating the interplay between a growing biofilm on a metallic surface and environmental supported stress corrosion. The biofilm model incorporates substrate diffusion, bacteria metabolism as well as biofilm development, making it possible to estimate the pH at the metallic surface. The biocorrosion model is based on strain driven dissolution. The final model iterates between biofilm development that changes the pH at the surface and biocorrosion that changes the geometry of the substratum.

Introduction

Biofilm research is an expanding area with wide applications all around us. Hence, there are many models describing biofilms in different environments. However, these models rarely focus on the impact biofilms have on the surface they are attached to. We want to combine the knowledge about biofilms with an interesting application, namely strain assisted biocorrosion on a metallic substratum. An initially flat surface is known to develop a characteristic waviness when exposed to mechanical stresses and a dissolving agent simultaneously [1]. In this experiment, we intend to simulate biofilm growth to obtain a pH profile. Knowing that pH affects the underlying metal, we then include this profile in the corrosion law of material model to study the evolution of the metallic surface.

Biofilm model

We used the model in [2] to acquire a pH profile across the biofilm. The model is based on the famous 1D-model from [3], with equations* for diffusion of substrates S_k

$$\frac{\partial S_k(t,z)}{\partial t} = \frac{\partial}{\partial z}\left(D_k \frac{\partial S_k(t,z)}{\partial z}\right) + r_k(t,z)$$

and development of bacteria f_i

$$\frac{\partial f_i(t,z)}{\partial t} + \frac{\partial}{\partial z}\Big(u(t,z) f_i(t,z)\Big) = \mu_i(t,z) f_i(t,z).$$

With the equation** for pH

$$\frac{H^3}{M_H^3} + H^2 \cdot \frac{\alpha+\beta}{M_H^2} + H \cdot \frac{\gamma+\alpha\cdot\beta-2K_1P_t-K_2C_t}{M_H} + \gamma\cdot(\alpha - 2P_t - C_t) = 0,$$

where $\alpha = [K^+] + [Na^+] - [Cl^-],\ \beta = K_1 + K_2,\ \gamma = K_1K_2,$

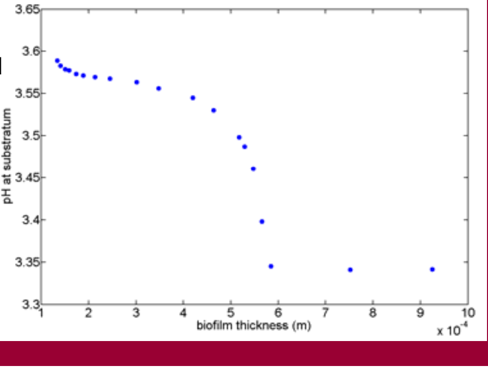
K_1, K_2 constants, $H, P_t, C_t, [K^+], [Na^+], [Cl^-]$ concentrations, we could calculate the profile.

* For constraints, conditions and rates, refer to [2].

** Our own freely derived version of eq. 5a, 5b and 5c in [2].

Results

We simulated biofilm growth from initial 25 μm of thickness for 300 days, updating the pH profile at every iteration. By changing the erosion parameter λ, we could achieve different biofilm thicknesses. The graph shows pH at the substratum (at day=300), depending on thickness.

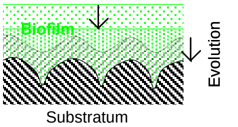


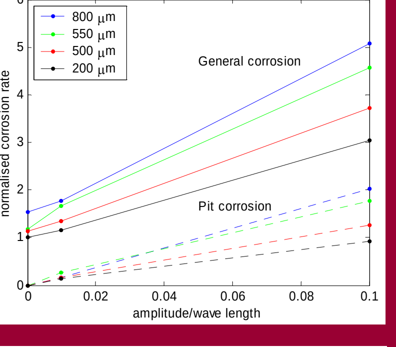
Material model

An adaptive finite element method is used to simulate the evolution of the surface of the metallic substratum due to corrosion in the form of material dissolution. The material is linear elastic and strained parallel to the surface. The corrosion rate v at each location along the surface is assumed as v=F(pH)(U_ε+U_γ). U_ε is the strain energy and U_γ a surface energy depending on the surface curvature [1]. U_ε is alway positive, but larger at pits and lower at tops. U_γ strives to flatten a surface. F(pH) is a linear function that increases with decreasing pH. The surface evolution is established by determining the mechanical strain, the curvature, and the biofilm thickness at each location. The biofilm is assumed to remain flat at its outer surface, even though the substratum develops a surface roughness.

Results

Semi-infinite substrata with an inital surface roughness in the form of a sinus wave were studied. The inital ratio amplitude/wavelength equaled 0 (flat), 0.01 (shallow) and 0.1 (deep), and biofilm thicknesses of 800, 550, 500 and 200 μm were considered. The general corrosion, defined as the dissolution rate at wave tops, and increasing depth of pits were monitored, see graph. As pits grow deeper, they may also sharpen.





Conclusions

The influence of pH on biofilm induced stress corrosion of a metallic substratum was successfully studied by combining a model for biofilm growth and a technique to simulate surface evolution due to dissolution of the metal. The pH profile shows three different regions – small, large, no – decrease with film thickness. Both the general and pit corrosion rates increase with surface roughness and film thickness. Pits may eventually sharpen to form stress corrosion cracks.

References

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