The Ecology of Microbial Corrosion

TIM FORD and RALPH MITCHELL

1. Introduction

Corrosion reactions may be induced or enhanced by microbial activity. The classic corrosion reaction is electrochemical, resulting in the dissolution of metal from anodic sites with subsequent electron acceptance at cathodic sites. Consumption of electrons varies, depending on the redox potential of the surface. In an aerobic environment, oxygen is the electron acceptor, forming metal oxides and hydroxides. At low redox potentials, protons become the electron acceptors, yielding hydrogen gas and other highly reduced products. The process of corrosion is accelerated by removal of the end products of the chemical reactions.

The involvement of microorganisms in this process has been difficult to evaluate. Analytic methods are designed to measure generalized corrosion, based on the Wagner-Traud theory for metal dissolution (Wagner and Traud, 1938). According to this hypothesis, corrosion is described as formation of random and dynamic cathodic and anodic sites on the metal surface (Little et al., 1984). The heterogeneity of microbial communities on metal surfaces results in the formation of anodic and cathodic areas that are distinct in space and time.

Investigation of microbially induced corrosion processes involves the study of adhesion of microorganisms to metal substrata, metabolism within the surface colony, and bacteria–metal interactions. Because corrosion rates are invariably accelerated beneath natural surface films comprising complex microbial communities, study of microbial interactions within these communities has become central to this research. Corrosion by sulfate-reducing bacteria has been intensively studied during the past 40 years. The literature has been extensively reviewed (Crombie et al., 1980; Iverson, 1981; Tiller, 1982; Gragnolino and Tuovinen, 1984; Hamilton, 1985; Pankhania, 1988). In this

TIM FORD and RALPH MITCHELL • Laboratory of Microbial Ecology, Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138.
review, we intend to focus on aspects of microbial corrosion that have received little attention despite an increasing awareness of their importance. In the section describing the sulfate-reducing bacteria, we will summarize the current knowledge of the ecology of these microorganisms in corroding systems. Oxidative processes, biochemical reactions related to microbial surface film formation, and interactions within communities will be discussed in greater detail.

Traditionally, the microorganisms involved in corrosion have been categorized into four distinct groups: (1) The sulfate reducers, (2) “slime-forming” bacteria, (3) iron-oxidizing bacteria, and (4) a miscellaneous group containing sulfur-oxidizing bacteria, fungi, and algae (Donham et al., 1976; Tatnall, 1981a). While this approach may have some functional utility for the nonmicrobiologist, it provides limited insight to the microbial ecologist searching for the fundamental microbial processes responsible for the biodeterioration of metals.

Both sulfate-reducing and iron-oxidizing bacteria may produce copious quantities of exopolymer (slime), and the traditional “slime-forming” pseudomonads may oxidize iron. In this review, we will separate the ecological processes involved in microbial corrosion into sections for ease of discussion. However, it is important to be aware that all processes described may be occurring simultaneously within the same surface community. The following topics will be discussed: the role of the surface microbiota, acid production, metal deposition and tubercle formation, hydrogen-consuming reactions, hydrogen-producing reactions, and thermophilic corrosion. In the concluding section, we will discuss current knowledge of microbial consortia and their interactions relating to corrosion.

2. The Role of the Surface Microbiota

Information about the complex ecology of microbial communities adhering to and growing on solid surfaces is essential if we are to understand the function of microorganisms in corrosion processes. In natural ecosystems, the surface microbiota is controlled to a large degree by the nature of the substratum and the available nutrients in the water column. The microbial community on metal surfaces is dependent on the chemistry of the solid and the liquid phases with which it is in contact. Hence, extremely specific microbial communities can be associated with individual metals, e.g., copper alloys and titanium (Marszalek et al., 1979; Berk et al., 1981; Walch, 1986; Ford et al., 1989).

No metal substratum appears to be totally immune from microbial colonization, although the rate of colonization may be strongly affected by a sloughing oxide layer (aluminum bronze), toxic ions (copper nickel), or inclusion of biocides. The nature of the biofilm is such that the glycocalyx, the extracellular microbial material generally consisting of extracellular polysaccharides (Costerton et al., 1981), can coat or bind toxic ions and biocides, rendering them ineffective. Briefly, the sequence of events in the adhesion of bacteria to surfaces is as follows (Maki and Mitchell, 1988):