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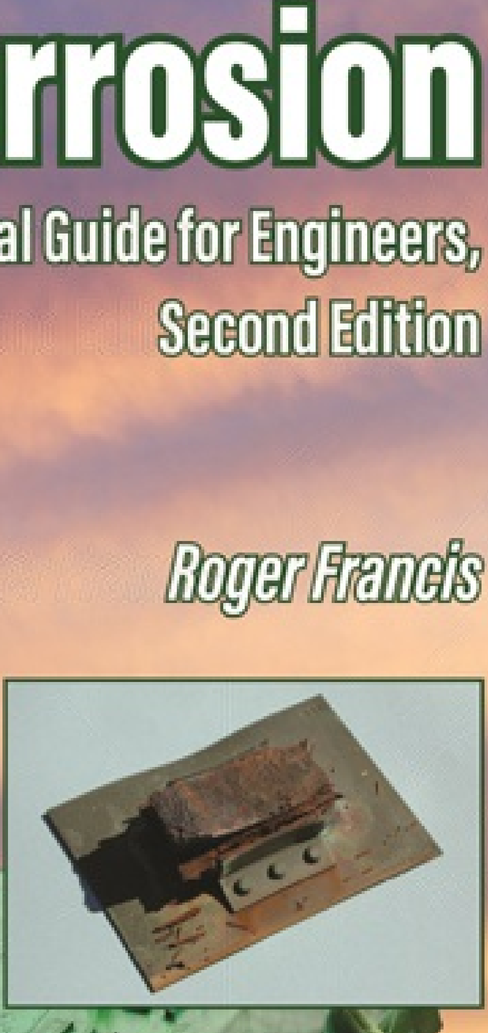
Galvanic Corrosion

A Practical Guide for Engineers, Second Edition

Roger Francis



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Preface

In my job as a corrosion engineer, I find that I get more questions about galvanic corrosion than any other area of corrosion. Although there is a lot of information in the literature on this subject, there is no single place where an engineer can go to find answers, and some of the references are in somewhat obscure places. Hence, I conceived the idea of writing this book to fill this gap. This book comprises not only many of these references but also some of my experiences in and opinions about the field of galvanic (bimetallic) corrosion. I have tried to make it easy to find information to solve specific problems rather than to present a more complex review of the science and engineering of galvanic corrosion.

During my quest for information, pictures, and case histories, I contacted many friends and colleagues, and I would like to take this opportunity to thank them all. Particularly, I would like to thank Hector Campbell, the late Brian Todd, Mick Schofield, Alan Turnbull, David Peacock, and the late Trevor Gooch (who passed away during the publication of this book and who I am very sorry didn't live to see it in print). Any differences between the information they gave me and the form in which it appears herein are my fault. I hope readers feel that the end result meets their expectations.

Roger Francis
2000

Preface to the Second Edition

When I originally wrote this book, every week I received numerous phone calls and e-mails concerned with galvanic corrosion. Since the publication of the first edition of this book, the number of galvanic enquiries I receive has nose-dived, and people often comment about how useful they find my book. With this in mind and because it has been 17 years since the first edition was published, NACE asked me to compile a second edition. The principles of galvanic corrosion have not changed, but more data have been published, and new materials have been engineered that can present galvanic corrosion problems. Hence, it was not a difficult decision to update the book.

Unfortunately, in the past 17 years, more of my friends and mentors have passed away, including Hector Campbell, to whom this book is dedicated. Fortunately, some of the remainder, including Mick Schofield, Alan Turnbull, and Bop Phull, have once again been helpful in providing data and checking the text. As before, any errors in the data are my fault, and I hope you think the new edition adds something to the collected lore on galvanic corrosion.

Roger Francis
2017

1 Introduction

Galvanic corrosion (bimetallic corrosion) occurs when two dissimilar metals are electrically coupled in an electrically conducting, corrosive fluid. Under these conditions, the rate of corrosion of one member of the couple is increased above that which would occur if the metal were exposed in isolation. Corrosion of the other member of the couple is reduced or may even cease altogether. The change in corrosion when two metals are coupled together is galvanic corrosion, and its severity may vary from a slight increase in corrosion of one component, of no significance for its continued performance, to a large increase in corrosion. This effect is often local, leading to rapid failure or perforation.

Galvanic corrosion is widespread in everyday life because of the large variety of metals used in engineering components. Very often, a component is bought as an individual item and, hence, could be fabricated from different materials than the rest of the engineered product; these components may be incompatible in service. It is the job of the corrosion engineer to be aware of potential corrosion problems and to ensure that these problems are properly addressed during design and procurement; otherwise, the consequences can be very expensive.

I am indebted to my friend Brian Todd for the following case history, which emphasizes this point. In several cargo ships with seawater cooling systems comprising galvanized steel piping and cast iron valves with manganese bronze stems, the system worked reasonably well, but the piping needed to be replaced every year or two because of corrosion, and so the piping material was changed to 90/10 copper-nickel (Unified Numbering System [UNS] C70600). Piping failures ceased, but problems then occurred with the valves owing to accelerated corrosion of the cast iron bodies. This problem was solved by replacing the valves with cast gunmetal (UNS C83600) bodies, but this solution caused a series of failures of the valve stems owing to dezincification of the manganese bronze (British Standard [BS] 2874[1] CZ114). This problem was solved by replacing the manganese-bronze stems with nickel-copper alloy 400 stems (UNS N04400). All of these failures caused a great deal of lost sailing time in addition to the costs of dry docking and purchasing and fitting each item. A senior engineer in the company calculated that initially fabricating the entire system in gold would have been cheaper than the piecemeal replacement actually undertaken! The moral of this case history is that corrosion engineers should *always* consider the *entire system* when evaluating materials to avoid problems of this sort.

I do not propose to explain the galvanic reactions that occurred in the above example, but after reading this book, readers will be able to work out the chemistry for themselves.

FIGURE 1.1: Piping and inlet water box for a multi-stage flash desalination plant.

FIGURE 1.2: Excessive galvanic corrosion of a carbon steel water box from a multi-stage flash desalination plant.

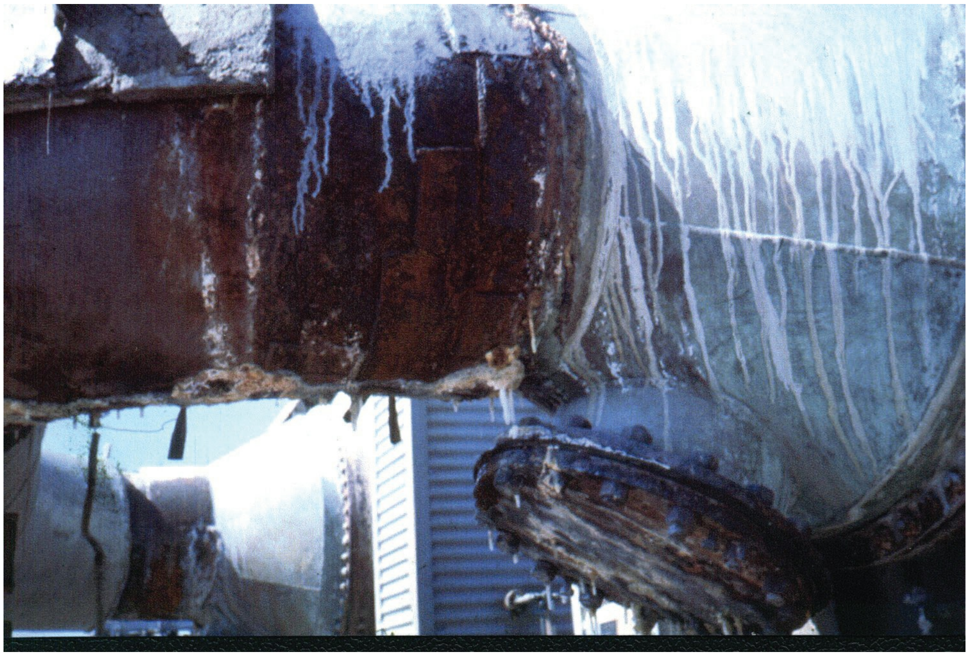

FIGURE 1.3: Water box and feed water pipe for a heat exchanger from a multi-stage flash desalination plant.

Figures 1.1, 1.2, and 1.3 of a multi-stage flash desalination plant in the Middle East show some examples of galvanic corrosion. Figure 1.1 shows the piping and inlet water box on one heat exchanger carrying poorly deaerated seawater. The tubes and tube plates were made from a copper alloy, and the original water box and seawater piping were made from carbon steel. Figure 1.2 shows one of the original water boxes that was put in the scrap heap because of excessive corrosion that occurred when the water box was coupled to the copper alloy tubes and tube plates. The water boxes were replaced with 90/10 copper-nickel (C70600) boxes, as shown in Figure 1.3. This photograph also shows several wooden pegs knocked into corrosion holes in the carbon steel pipe. This is another case of not considering the whole system when contemplating a materials change. To prevent corrosion, the piping should have been replaced with lined carbon steel or copper-nickel.

Galvanic corrosion is controlled by several factors, which are not always easy to determine in practice. The intention of this book is to create guidelines for engineers, so the electrochemical theory has been kept to the minimum necessary to understand what is happening in specific cases. A simple knowledge of electrochemical potentials and polarization curves will suffice to follow these guidelines.

Chapter 2 discusses factors that affect galvanic corrosion, and Chapter 3 briefly reviews the general galvanic behavior of the major metal and alloy groups. This chapter now includes a discussion of carbon-reinforced composites and some common cobalt-based alloys, as well as the potential galvanic problems with high-velocity oxygen fuel coatings. The following five chapters deal with galvanic corrosion in some common industrial environments and have been expanded to include a well-known case history of galvanic corrosion in the atmosphere and a review of recent data in hot caustic solutions. The final two chapters discuss corrosion with three dissimilar metals and the prevention of galvanic corrosion, respectively.

If this document is read from beginning to end, it will be noticed that there is a certain amount of repetition. This is because it is expected that most readers will dip into sections relevant to their current problem, and they will not wish to follow references to other chapters. Where the point at issue requires more lengthy discussion, reference to other chapters has been unavoidable.

This guide refers to a range of commonly used engineering alloys, usually by their generic name or alloy type. For those unfamiliar with any of these, there are lists in the Appendix, in which alloys are grouped by type, e.g., copper alloys, with the nominal composition. Specific alloy designations typically follow the UNS.[2] In a few cases, national designations have been used where there is no UNS equivalent, and the Aluminum Association four-digit designations have been used for aluminum alloys because of the dominance of this system in the industry. A simple guide to change these into UNS numbers has been included in Chapter 3.

REFERENCES

1. BS 2874, “Copper and Copper Alloys: Rods and Sections (Other than Forging Stock)” (London: British Standards Institute, 1986).
2. *Metals and Alloys in the Unified Numbering System* (Warrendale, PA: SAE; West Conshohocken, PA: American Society for Testing and Materials [ASTM], 2012).

2 First Principles

When a metal is immersed in an electrically conducting liquid, the metal takes up an electrode potential; this is known as its corrosion potential. This potential is determined by the equilibrium between the anodic and cathodic reactions occurring on the surface, and it is measured with reference to a standard electrode, such as the SCE.

Bimetallic corrosion occurs when two metals with different potentials are in electrical contact while immersed in an electrically conducting corrosive liquid (electrolyte). Because the metals have different natural potentials in the liquid, a current will flow from the anode (more electronegative) metal to the cathode (more electropositive) to equalize the potentials. This will increase the corrosion on the anode (Figure 2.1). This additional corrosion is bimetallic corrosion, which is also known as galvanic corrosion, dissimilar metal corrosion, or contact corrosion. These terms are used interchangeably throughout this book.

Generally, the reactions that occur under bimetallic corrosion are similar to those that would occur on a single, uncoupled metal, but the rate of attack is increased, sometimes dramatically. With some metal combinations, the change in the electrode potential in the couple compared with the uncoupled potential can induce corrosion that would not have occurred in the uncoupled state. An example of this is pitting corrosion of passive metals, such as stainless steels, when the potential is raised above the potential at which pitting initiates. In some environments, the change in potential of the cathode in the couple, compared with the uncoupled state, can also introduce problems. An example of this is the hydrogen embrittlement of ferritic steels owing to evolution of hydrogen at the cathodic site.

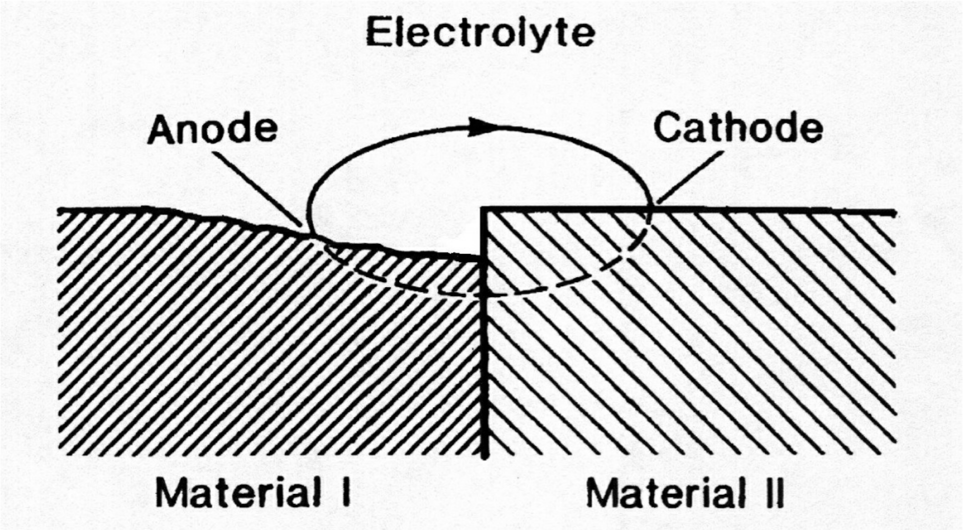

FIGURE 2.1: Schematic diagram of a galvanic corrosion cell.

The effect of coupling two metals together increases the corrosion rate of the anode (initially the metal with the more electronegative potential) and reduces, or even suppresses, corrosion of the cathode (initially the metal with the more electropositive potential). Hence, coupling a component to a sacrificial anode can prevent corrosion, and this is the principle of cathodic protection. This process is not discussed in detail in this book, and those who require more information on this subject are referred to specialist texts.

When a metal is corroding, two processes are occurring. One is the dissolution of metal at the anode, e.g., iron:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e^-$$

This must be balanced by a cathodic reaction, which in most neutral and alkaline liquids is the reduction of dissolved oxygen:

$$\mathrm{O_2} + 2\mathrm{H_2O} + 4e^- \rightarrow 4\mathrm{OH}^-$$

In acidic liquids, the cathodic reaction is often the reduction of hydrogen ions to hydrogen gas:

$$2\mathrm{H}^+ + 2e^- \rightarrow \mathrm{H_2}$$

Other cathodic reactions can occur in deaerated environments, and one example is solutions containing sulfur and its compounds. There is a range of partially oxidized sulfur species (e.g., thiosulfate or dithionate) and of elemental sulfur, and reduction of one or more of these species can be the principle cathodic reaction in corrosion, e.g., sour process brines in the oil and gas industry.

$$\mathrm{S}^0 + 2\mathrm{H}^+ + 2e^- \rightarrow \mathrm{H_2S}$$

Under uncoupled corrosion conditions, the anodic and cathodic reactions occur at small, local areas on the metal surface. In a bimetallic couple, the cathodic reaction is mostly, or totally, on the electropositive member of the couple, and the anodic reaction is mostly, or totally, on the electronegative member of the couple.

The basic requirements for bimetallic corrosion are:

1. An electrolyte bridging the two metals. The electrolyte may not be aggressive to the individual metals when they are not coupled and may be in the form of a bulk volume of solution, a condensed film, or a damp solid such as soil, salt deposits, or corrosion products.
2. Electrical connection between the two metals. This electrical connection usually arises from direct physical contact but also can arise where electrical continuity is established between two metals, e.g., by an insulation-coated conductor, by structural metal work, or by electrical grounding systems. It is not necessary for the metal junction to be immersed in the electrolyte.
3. A sufficient difference in potential between the two metals to provide a significant galvanic current.
4. A sustained cathodic reaction on the more noble (more electropositive) of the two metals by one of the mechanisms described above; in most practical situations, this reaction is the consumption of dissolved oxygen.

Many factors affect galvanic corrosion, including electrode potential, cathodic efficiency, area ratio,