The effect of protective coatings on galvanic corrosion for bolted components

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Abstract

The increasing demands for better fuel-efficiency have led the automobile industry to use lightweight metals such as aluminum and magnesium in conjunction with conventional metals such as steel. Galvanic corrosion is the unfortunate result of this “mixed metals” usage. The automobile companies rely primarily on proving ground testing to evaluate the severity of corrosion. Such a procedure is costly and time consuming. The objective of this project is to explore the feasibility of using computer simulation to predict galvanic corrosion in automobile environments. The BEASY code has been chosen for this project. There are two parts in the study. The first part is to validate BEASY and the second part is to perform the bolted component corrosion simulations. This study shows that with as little as 2 mm of protective coatings, the peak corrosion rate can be reduced by as much as 70%. The BEASY code is a potentially useful tool to estimate the corrosion rate if an accurate representation of a current density and electrical potential relationship - the polarization curve - of the metals of interest can be experimentally determined.

Introduction

Corrosion is the destructive result of chemical reactions between a metal or metal alloy and its environment and presents some of the most costly problems to the automobile and other industries. The cost of corrosion in the United States in 1975 alone was estimated to be $82 billion, or 4.9% of the United States’ gross national product [1]. Because of the recent demands for better fuel-efficiency, more lightweight metals such as aluminum and magnesium are utilized in conjunction with conventional metals such as steel. This increasing “mixed metals” usage further increases the cost of corrosion in addition to the corrosion costs that already exist.

Galvanic corrosion [2] is one type of corrosion and can occur when two different metals are coupled in the presence of a corrosive solution. Therefore, galvanic corrosion is the undesirable result of this “mixed metals” usage. The
automobile companies rely primarily on proving ground testing to evaluate the severity of corrosion. Such a procedure is costly and time consuming. The objective of this project is to explore the feasibility of using computer simulation to predict galvanic corrosion in automobile environments. There are two parts in the study. The first part is to validate an appropriate computer code capable of performing galvanic corrosion. The second part is to predict galvanic corrosion of bolted components in automobile environments.

There are two types of simulation tools available, experimentally and analytically based tools. The experimentally based tools include expert systems and neural networks. They rely heavily on test data, previous experience and are problem specific and very easy to use. Finite difference, finite element and boundary element methods are the analytically based tools. Since galvanic corrosion occurs on the surfaces of bimetals, the boundary element method appears to be more appropriate than the other methods for corrosion simulations.

Most early corrosion simulations were carried out by the oil and gas industries. Their primary structures of interests are offshore platforms and pipelines. They generally use the experimentally based tools. The marine industry conducts limited numerical corrosion studies. The automobile companies have done very little corrosion simulation. The galvanic corrosion in automobile environments is quite different and is more difficult to simulate because the bimetals are coupled with thin electrolytes.

Munn [3] was a pioneer in the modeling of galvanic corrosion. He used the mathematical analogy between electrical and thermal conduction. Consequently he was able to solve corrosion problems with a finite element program [4] having heat transfer capability. He solved several problems including the beaker and tank problems, which are used as benchmark problems for validation.

In the beginning of this investigation, BEASY [5] was the only galvanic corrosion software available. It is a boundary element computer code. The main feature of the boundary element method is that only surface elements are needed as compared to the finite element method where volume elements are required. So the boundary element method offers a significant modeling time advantage over the finite element method for corrosion studies.

For validation purposes, we compare BEASY results with the results of the beaker and tank problems in [3]. We also compare BEASY results with those from a computer code - ANSYS [6] using its heat transfer option. After the BEASY code has been properly validated we then proceed with our bolted connection simulations.

Because corrosion simulations and the concept of boundary element method are relatively new in automobile applications, we first briefly review galvanic corrosion formulation within the context of the boundary element method. We then give a brief description between the corrosion problems and the corresponding heat transfer problems. Some of the shortcomings of using heat transfer to simulate corrosion are also stated. Subsequent sections cover the results of the validation and the presentation of bolted connection galvanic simulations. The final section offers summaries and conclusions.
Boundary element (BE) and finite element (FE) methods

Both the BE and FE methods lead to an integral equation, which consists of a volume integral and a surface integral in three-dimensional (3D) space. In the FEM, both integrals are discretized, creating volume elements in the interior and surface elements on the surface of a 3D model. In the BEM, the volume integral is further converted to another surface integral through the so-called fundamental solutions. These fundamental solutions are nothing more than the response functions at some locations called field points due to a unit input such as a unit load or displacement at other locations called source points. As a result, the original integral equation contains only surface integrals. Therefore we need to generate surface elements instead of volume elements in the BEM. It is very difficult and time consuming to generate volume elements. Either too many elements are required or the aspect ratio of the elements is excessive, introducing undesirable errors. It is, however, much easier to generate two-dimensional (2D) surface elements. If it is a 2D model, then the surface elements degenerate to line elements.

The primary unknowns, such as electric potentials and temperatures, to be solved are at the nodes for both methods. The derived quantities, such as current densities and heat flux, are evaluated at the centroid or the integration points and then extrapolated to the nodes in the FEM. But the same quantities, however, are directly calculated on the surface without extrapolation in the BEM. So the BE results are more accurate than the corresponding FE results. Since galvanic corrosion occurs on the boundary, the BE approach is much more attractive than the FEM.

In the BEM, the transformation of the volume integral to a surface integral depends on the existence of fundamental solutions. For most nonlinear problems, a fundamental solution does not exist. In this case we need to mesh the interior of the nonlinear portion of the model. Consequently BEM will lose its attractiveness. Those interested in a more detailed comparison between the BE and FE methods are referred to [7].

Galvanic corrosion formulation in BEASY

The governing equation for electrostatic simulation is the Laplace equation

\[ \Delta \Delta \phi = 0 \]

in the electrolyte domain \( \Omega \) subjected to appropriate boundary conditions on the boundaries \( \Gamma_i \) where \( i = 1, \ldots, n \). The unknown \( \phi \) is the electrical potential on the boundary and within the electrolyte. Typical corrosion boundary conditions are given by the following equations.
\[ \phi = \phi_0 \text{ on } \Gamma_1 \]  
\[ q = q_0 \text{ on } \Gamma_2 \]  
\[ \phi = f_a(q) \text{ on } \Gamma_{3a} \text{ and } \]  
\[ \phi = f_c(q) \text{ on } \Gamma_{3c} \]  
where \( q \) is current density and can be calculated from equation (3)

\[ q = -\kappa \Delta \phi. \] (3)

\( \kappa \) in equation (3) is electrical conductivity of the electrolyte and is assumed to be a constant in this investigation.

Corrosion is an electro-chemical process, but the Laplace equation (1) contains no information about the chemical reactions of the corrosive metals. The coupling of the electrical potential with the chemical reactions is through the boundary conditions imposed upon the anode, equation \((2c)\) and the cathode, equation \((2d)\). The relationship between the current density \( q \) and the potential \( \phi \) is called polarization in corrosion. The polarization is a complex function of types of metals and electrolyte properties as well as temperatures and flow velocities of the electrolytes. The accuracy of the galvanic corrosion simulations depends on realistic polarization information obtained from experiments. Polarization curves for different metals are depicted in Figure 1 [2].

Corrosion occurs at the anode. The anodic current density distribution can be determined on the surface of an anode from BEASY. The corrosion rate mpy, mil per year, can be obtained from the Faraday Law [8],

\[ \text{mpy} = \frac{129 \times w \times q}{n \times d}. \] (4)

In equation (4), \( w \) is the atomic weight of the corroding metal, \( q \) (milliamp/cm\(^2\)) is the current density, \( n \) is number of electrons lost per atom, and \( d \) (g/cm\(^2\)) is the density of the corroding metal.

**Thermal analogy to corrosion**

The differential equation that governs electrostatics in equation (1) also governs heat conduction and many other phenomena. In equation (1), if we consider \( \phi \) as temperature, \( q \) as heat flux we will have a heat transfer problem. The material constant \( \kappa \) becomes the thermal conductivity. The heat convection boundary conditions are similar to the polarization corrosion boundary conditions, equations \((2c \text{ and } 2d)\) with the following exceptions. The polarization relates the potential \( \phi \)-the temperature in heat conduction-explicitly as a function of current density \( q \)-the heat flux in heat conduction. The heat convection boundary conditions are, however, imposed by the following equation [6],

\[ q = h(\phi)/\phi_b \times (\phi - \phi_b). \] (5)

where \( h(\phi)/\phi_b \) is a pseudo film coefficient, \( \phi \) is the temperature on the boundary and \( \phi_b \) is the bulk temperature in the surrounding fluid. The above equation becomes equation (6)

\[ q \sim -h(\phi). \] (6)
if $\phi_b >> \phi$. The resulting heat convection is similar to the corresponding polarization in equations (2c and 2d). Therefore we can solve corrosion problems using a thermal analogy by applying the boundary conditions similar to equation (5) and imposing

$$\phi_b >> \phi.$$  \hspace{1cm} (7)

One of the shortcomings of using a thermal analogy is the condition required by equation (7). Since we do not know how large a value of $\phi_b$ we should use, we have to use a trial and error procedure. This time-consuming procedure requires repeated solutions of the same problem with different values of $\phi_b$ until a converged solution in $\phi$ is found.

### Validation

A beaker and tank problems are used to assess the accuracy of the BEASY for galvanic corrosion simulations. McCafferty [9] derived an analytic solution for a beaker with electrolyte inside. The anode and cathode are located on the inner and outer base of the beaker as shown in Figure 2. He assumed the following linear anodic and cathodic polarization,

$$q_a = 0.04\phi_a$$

and

$$q_c = 0.04*(\phi_c - 1)$$
The electrical conductivity \( \kappa \) was 0.04 mho/cm. The inner and outer radii of the cathode were 0.5 and 1.0 cm, respectively. The height \( H \) of the electrolyte was 0.5 cm. An axisymmetric model was used.

Figure 3 is a potential graph where we plot the potential on the surfaces of the anode and cathode as a function of radii of the beaker from McCafferty's analytic solution as well as from BEASY and ANSYS results. The BEASY solution is in good agreement with both the analytic and ANSYS solutions.

The tank problem was investigated numerically and experimentally by Munn [3], and is a demonstration of an iron-zinc galvanic couple. Figure 4 describes the geometry of the tank where an iron plate and a zinc rod were submerged in seawater. The dimension of the tank normal to the paper had a unit length. Munn used an electrolyte conductivity of 0.04 mho/cm, the iron polarization curve as described in Figure 1, and a zinc fixed potential of -1005 mV.

Munn’s experimental potential results for the tank problem are shown in Figure 5. In this validation, the problem is first solved with BEASY. Figure 6 shows the BEASY results. The same problem is then analyzed with ANSYS heat transfer option where an accurate solution for the corresponding corrosion simulation requires convergent studies. To convert the corrosion problem to a corresponding thermal one, it is necessary to set the “bulk temperature” \( \phi_b \) equal to a value larger than the “surface temperature” \( \phi \) in equation (7). Figure 7 describes the convergence of the temperature as a function of the bulk temperatures. For this tank problem, Figure 7 shows the minimum bulk temperature must be equal to 1e+10. The converged temperature or the potential plot is given in Figure 8. BEASY results compare well with ANSYS corresponding heat transfer results. There is also a reasonably good agreement between the numerical solutions and Munn’s experimental results. Exact agreement, however, cannot be expected due to errors introduced in obtaining input data from the polarization curve in Figure 1.
Figure 5: Experimental Potential Results for the Tank Problem

Figure 6: BEASY Potential Result for the Tank Problem
Bolted component simulations

The axisymmetric model for the bolted component simulations is shown in Figure 2. It is a cylinder with a metallic base. The electrolyte in the cylinder is 3% salt solution and its height $H$ is 12.7 cm. The base has a cathode in the center and an anode surrounding the cathode. The inner and outer radii of the cathode are 0.635 cm and 4.950 cm, respectively. The cathode is used to simulate a fastener such as a steel bolt. The anode represents the component being joined together. Around the cathode we install protective coatings as electrical insulators of thickness equal to 0.0, 0.0859 and 0.1793 cm. We use four different galvanic couples. The metals used for the bolt and for the component are tabulated in the table below.

<table>
<thead>
<tr>
<th>Cathode-Bolt</th>
<th>Fe</th>
<th>Fe</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode-Component</td>
<td>Mg</td>
<td>Zn</td>
<td>Al</td>
<td>Al</td>
</tr>
</tbody>
</table>

The BEASY results for typical radial current density distributions for a steel bolt and a zinc component with protective coatings of 0.0, 0.0859 and 0.1793 cm are compared in Figure 9 where “Dr” represents the thickness of protective coatings. The figure demonstrates a peak anodic current density drop in the zinc component from -0.630 mA/cm$^2$ without protective coatings to -0.196 mA/cm$^2$ with 0.0859 cm protective coatings. This is a reduction of 69% in current density with just 0.0859 cm protective coatings. Figure 10 summarizes the effect of protective coatings on reduction of peak current densities for various galvanic couples. Figure 12 shows that it is very effective to install thin protective coatings around a bolt to reduce corrosion rates. Depending on different galvanic couples, with 0.0859 cm protective coatings the reductions in corrosion rates range from 9% for Fe-Al to 69% for Fe-Zn. Doubling the protective coatings to 0.1793 cm will not significantly further reduce corrosion rates.
Conclusions

We have compared BEASY results with two benchmark problems, the beaker and tank problems. We also obtain a corresponding thermal solution for those problems. The beaker problem has an analytic solution. These analytic and thermal solutions compare well with BEASY results. Experimental results are available for the tank problem. The numerical results agree very well with each other and also are in reasonably good agreement with the experimental results. We do not recommend thermal analogy to be used to solve corresponding corrosion problems because this approach inherently involves a
time-consuming trial-and-error procedure. We conclude that BEASY is a potentially useful tool capable of performing galvanic corrosion.

In this study we use an axisymmetric model to study the effect of protective coatings on corrosion rates of bimetal bolted components. Because of a lack of experimental polarization information, we use polarization curves from the literature. The simulation results thus obtained are useful only for comparison purposes. We have found from this investigation that a small amount of protective coatings installed around a fastener can reduce the peak corrosion rate as much as 69% for some galvanic couples. Further increases in thickness, however, will not substantially reduce the corrosion rate.

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References