

Simulation of Galvanic Corrosion of Aluminum Materials for Vehicles

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ABSTRACT

A simulation technology has been developed to enable prediction of galvanic corrosion in chassis parts where two different materials, iron and aluminum, come into contact with each other. When polarization curves representing a corrosive environment are input, this simulation technology calculates the corrosion current to flow and outputs the volume of aluminum corrosion to be formed near the iron-aluminum interface. The simulation makes it possible to predict the depth of corrosion that may occur in automobiles in the market.

INTRODUCTION

Replacing iron materials with aluminum ones is a means to reduce weight. On the other hand, suspension and other parts exposed to a harsh corrosive environment are likely to suffer galvanic corrosion, so it is important to evaluate the corrosion resistance of these parts. In component development, parts under evaluation are often exposed to an outdoor environment for a long time, or corrosion acceleration tests are conducted using testers calibrated to represent actual conditions in the market. These methods, however, require several months to several years of test time. As a preliminary study to this research, an extensive search was made for existing computer aided engineering (CAE) methods that would enable the above evaluation in a shorter time. As a result, software for computing galvanic corrosion in an immersion environment, such as in seawater, was found, but this software was not capable of simulating corrosion in automotive applications. This research was therefore made to quickly evaluate and prevent galvanic corrosion of aluminum materials that may occur in the market, and a simulation technology has been developed to substitute for the conventional acceleration test.

TEST CONDITIONS AND METHOD

TEST MATERIALS

The following materials were used:

- Aluminum A356
- Steel bolt material SCM435 (equivalent to ISO: 34CrMo4)

CORROSION ACCELERATION TEST

The cyclic corrosion tester (CCT) made by Suga Test instruments Co., Ltd. was used for the acceleration test of corrosion. The test was conducted by repeating the cycle of CCT conditions shown in [Table 1](#).

SPECIMEN AND CORROSION CURRENT MEASUREMENT

[Fig. 1](#) is a cross section of the specimen used for measuring corrosion current. The specimen was an aluminum plate to which a steel bolt was fastened, with a Teflon sheet inserted in between to insulate the contact surface. The two parts were electrically connected by a wire, and the corrosion current was measured during the CCT test with a zero-shunt ammeter.

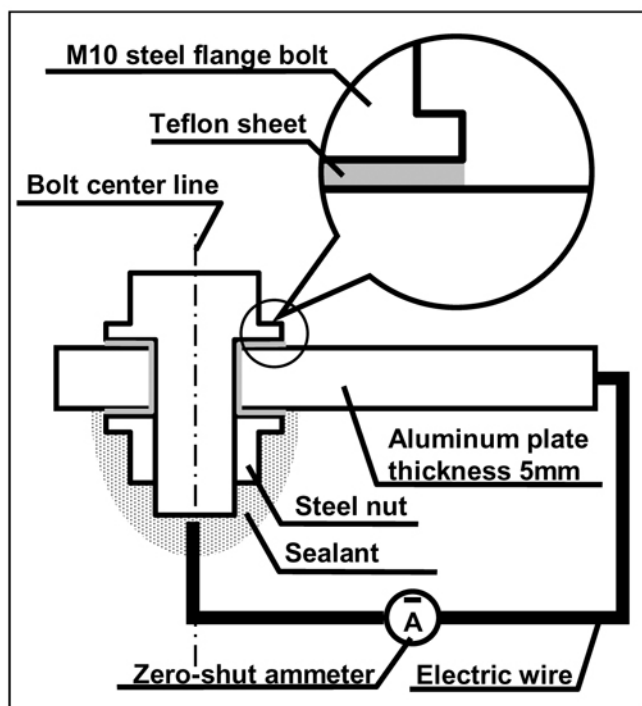


Fig. 1. Cross section of specimen for corrosion current measurement

CORROSION MORPHOLOGY MEASUREMENT

After corrosion occurred, the bolt was detached from the aluminum plate. Then, the corrosion product ($\text{Al}(\text{OH})_3$) was removed by soaking the plate in a solution of 1-L H_3PO_4 85wt% and 340-g CrO_3 in 10-L distilled water. Immersed in this solution, the aluminum plate underwent ultrasonic cleansing at 60°C . The plate surface was observed every hour until it was completely free of the corrosion product, and then the plate was washed with tap water. After washing and drying, the corrosion morphology on the aluminum specimen was observed with the Conoscan 3000 non-contact 3-dimensional measurement system (Optical Metrology Ltd.). The measurements were plotted to obtain average corrosion depths along each concentric circle of the corroded area vs. their radial distances from the interface between the steel bolt and the aluminum plate. The measured data was then compared with the simulated result.

SIMULATION SOFTWARE

In this research, 3D-Cafe by the Mizuho Information & Research Institute, Inc. was used as the solver to simulate the corrosion current. This software solver calculates the rate of corrosion using the boundary element method (Reference 1). Physical properties necessary for the simulation are the polarization curve, ion valence, specific gravity, and mass per mol of metal. Another physical property needed is the electric

conductivity of the solution used to simulate a corrosive environment. Polarization curves and electric conductivity were measured in this study.

POLARIZATION MEASUREMENT

An aluminum specimen $50 \times 15 \times 2$ mm in size was taken from the material undergoing the corrosion test. The specimen was polished with #600 emery paper. Then, the entire surface except for a 1 cm^2 test area was masked with silicone rubber. Table 2 lists the specifications of the test solution used for measuring polarization curves under each condition. Ag/AgCl was used as the reference electrode, and polarization was measured by sweeping voltage at 0.02 V/min .

ELECTRIC CONDUCTIVITY MEASUREMENT

Electric conductivity was measured under the conditions in Table 2 using an electric conductivity measuring instrument. Table 3 lists the measurements under each condition.

PROBLEMS IN SIMULATION

Regarding the corrosion current density and corrosion morphology, data obtained in the CCT corrosion test was compared with the calculations made with 3D-cafe. Table 4 and Fig. 3 show the comparison. Fig. 2 is a one-dimensional simulation model of the specimen; this model is axially symmetric to the bolt center line. The radial distance from the bolt is a variable. In this model, the steel bolt and the aluminum plate are placed in a salt water solution, and the contact between the steel boundary and the aluminum boundary indicates the aluminum-steel (bolt) interface. Simulation was made for a model dipped in salt water. Table 4 lists the measured corrosion current density and the simulated values. Fig. 3 compares the measured cross-section profile of the specimen corroded after an 816-hour CCT test and the corrosion profile simulated for the model in the same condition. The simulation differed from the measurement in the following two respects:

- Corrosion current density: The simulated corrosion current density was lower than the measurements.
- Corrosion morphology: The simulation resulted in a form of galvanic corrosion evenly spread over the aluminum surface. On the other hand, after 816-hour CCT testing, the specimen had localized corrosion within a 3.1 mm periphery of the aluminum-steel (bolt) interface. The corrosion was deepest at a distance of 0.65 mm from the interface. In addition, the

simulated depth of galvanic corrosion was much smaller than the depth observed after the CCT test.

To solve the above two problems, a galvanic corrosion simulation technology was developed to make predictions that would correlate well with measurements.

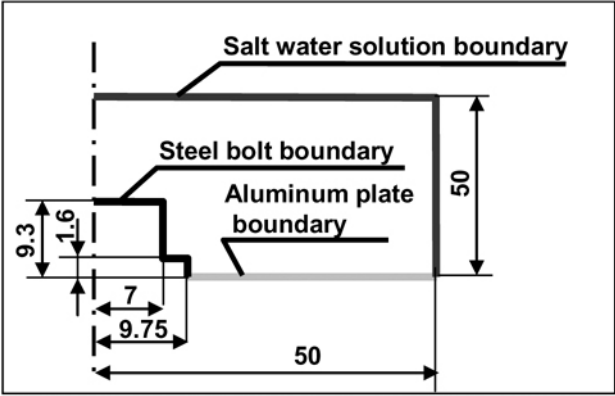


Fig. 2. Simulation model

Table 4. Comparison of corrosion current density

Condition	Simulation	Measured value
Salt spray	20μA/cm ²	120μA/cm ²
Drying	10μA/cm ²	100μA/cm ²
Saturation	10μA/cm ²	100μA/cm ²

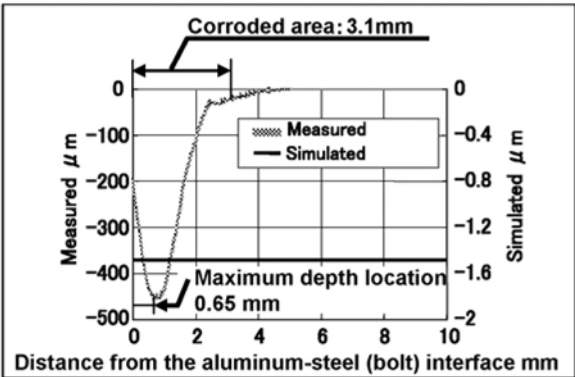
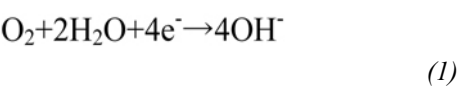


Fig. 3. Corrosion profile after 816-hour CCT test

CORROSION CURRENT DENSITY

When iron coupled with aluminum is immersed in salt water, a corrosion current flows between the two metals, causing galvanic corrosion. The source of this current is a cathodic reaction in which oxygen reduction occurs on the iron surface (equation 1).



The corrosion current varies depending on two factors: One is the area of the cathode, and the other is the current density at the time of iron cathode polarization. In this experiment, the bolt head works as the cathode, so the cathode area is identical for both the simulation and the actual corrosion test. Accordingly, attention was paid to the current density at the time of iron cathode polarization, and differences between the corrosion current density measurements and the simulated values were examined.

When galvanic corrosion occurs on aluminum in contact with iron, the corrosion potential and the corrosion current density is determined by a point where the iron cathode curve intersects the aluminum anode curve, as shown in Fig. 4. In our polarization measurement, the corrosion potential was -670 mV and the corrosion current density was 20 μA/cm² at this intersection. Iron cathode polarization occurred in a region where the current density hardly changed at all in response to changes in the potential. Current values in this region are called oxygen diffusion current, which maintains equilibrium between the amount of oxygen reduced on the iron surface and the amount diffused in the solution. In other words, the cathodic reaction on the iron surface is principally determined by the amount of oxygen reaching from the air-solution boundary to the iron surface by means of diffusion through the solution.

Polarization curves were measured using a bulk solution because the specimen had to be immersed in salt water. Here, the term bulk solution refers to a solution filled in a test container. In contrast, salt water formed a thin water film on the specimen surface during the CCT test (Fig. 5). In this paper, this state is called a water film environment. The oxygen diffusion distance is shorter in a water film than in a bulk solution, resulting in a greater amount of oxygen diffusion. This is assumed to cause a more active cathodic reaction and increased oxygen diffusion current. To prove this assumption, polarization was measured in a bulk solution into which hydrogen peroxide was added to represent a water film environment, because measurement is not possible in an actual water film. In the solution, hydrogen peroxide quickly supplements oxygen consumed by oxygen reduction on the iron surface, and thus a water film environment is reproduced. Polarization curves in a water film environment were obtained this way.

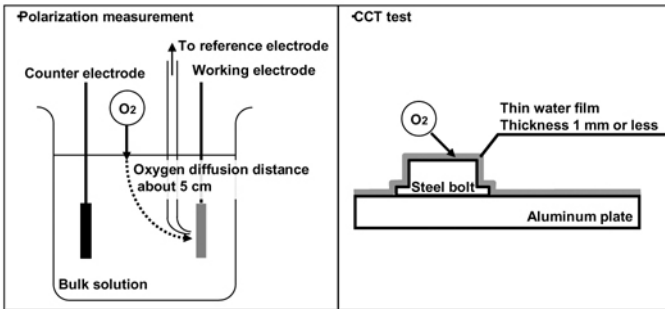


Fig. 5. Salt water state

Hydrogen peroxide was added to the solution under the conditions shown in Table 2, and steel polarization was measured. Fig. 6 plots the relation between hydrogen peroxide concentrations and current density values at a corrosion potential of -670 mV.

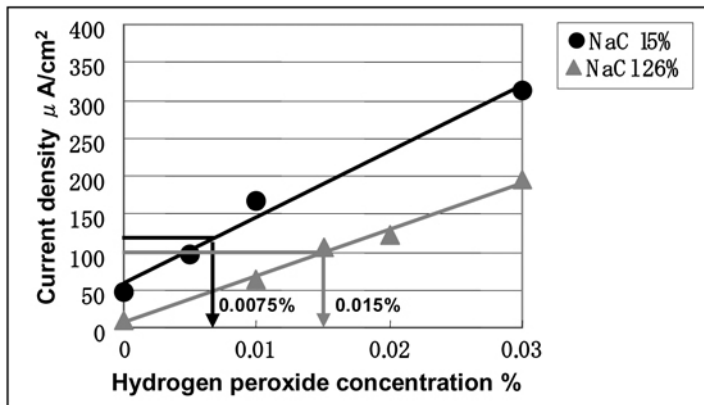


Fig. 6. Hydrogen peroxide concentration vs. current density

The hydrogen peroxide concentration and the current density are in proportion to each other, as shown in Fig. 6. Thus, it was possible to read the hydrogen peroxide concentration value corresponding to the current density measured under each test condition. Next, polarization curves were obtained from measurements made at the concentration values read from this figure. The obtained polarization curves were input to simulate the corrosion current density. As shown in Table 5, the simulated corrosion current density values are in close agreement with the measured values. This was achieved by adding an appropriate amount of hydrogen peroxide to the test solution and measuring polarization curves in this solution.

CORROSION MORPHOLOGY

A program for reproducing corrosion morphology was made in three steps by comparing the actual corrosion with the

simulated results. The first step reproduced the extent of galvanic corrosion, and the second stage the locations of severest corrosion. In the third step, the total amount of corrosion was corrected to reproduce corrosion morphology.

REPRODUCTION OF CORRODED AREA

Electric resistance increases as an electric wire becomes thinner. Similarly, electric resistance increases as a water film becomes thinner, so the extent of galvanic corrosion on the aluminum plate becomes smaller as the water film becomes thinner. Also the corrosion current flows in a greater concentration adjacent to the aluminum-steel interface. Fig. 7 shows the simulation of how the area and depth of corrosion change in response to changes in water film thickness. In this study, a surface area on which the depth of corrosion is 5% or more of the maximum depth is defined as a corroded area. Fig. 8 shows the relation between the corroded area distances from the interface (0 in the figure) and the water film thickness. As shown in this figure, the corroded area expands farther as the water film becomes thicker. We used Fig. 8 to read the water film thickness corresponding to the corroded area distance measured on a specimen CCT tested for 816 hours. We then set the read thickness value, $30\text{ }\mu\text{m}$, as the water film thickness of the simulation model.

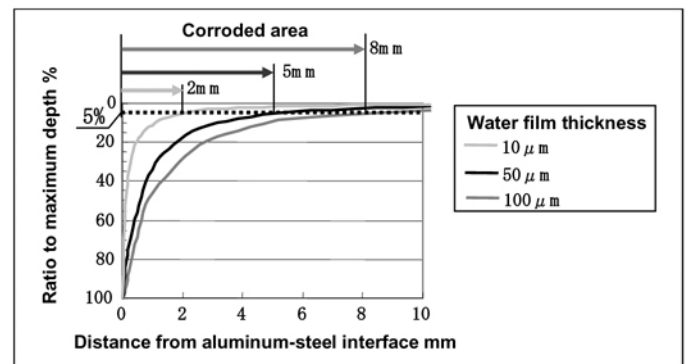


Fig. 7. Influence of water film thickness on simulation

REPRODUCTION OF LOCATION OF DEEPEST CORROSION

Fig. 9 compares the simulated corrosion profiles with the measurements of the specimen CCT-tested for 816 hours and 1782 hours. The horizontal axis indicates the radial distance of the corroded area from the aluminum-steel (bolt) interface, and the vertical axis indicates the depth of galvanic corrosion. The simulation predicted deepest galvanic corrosion would occur near the interface, whereas the measurements indicated the location of deepest corrosion farther away from the interface. This distance became greater as CCT test hours