Defending Automotive Components Against Corrosive Destruction

Simulation of hybrid material car components and joints enables innovative design for corrosion protection in automotive applications.

by **LEXI CARVER**

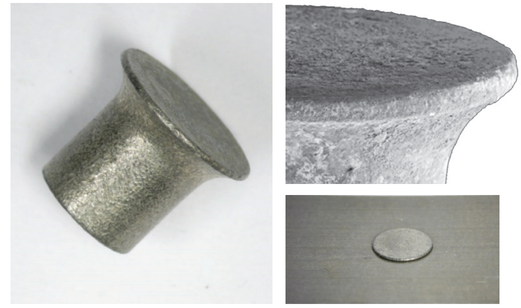

FIGURE 1. Left: Clean rivet. Top right: Rivet showing magnesium hydroxide deposit (white growth) due to corrosion. Bottom right: Magnification of a rivet in a test sheet.

Glance at a bridge's support beams while stuck in traffic, examine the door of an airplane while waiting to board, or check around the hood of your car, and you will see the small, round heads of rivets holding different surfaces together. Found in metal-bodied vehicles and support structures across the transportation industry, these rivets usually go unnoticed despite their role in joining components that withstand enormous mechanical stress. Some cars contain over 2,000 of them.

As automotive design trends move toward lightweighting and the use of multiple metals, so do the questions surrounding a destructive, invisible culprit whose handiwork is often only noticed once it is too late: corrosion.

➔THE CLASH OF METAL-ON-METAL: GALVANIC CORROSION

Galvanic corrosion is an omnipresent process that costs the automotive industry billions of dollars each year. Caused by chemical reactions between different metals coming into contact with one another, this type of corrosion in some cases is visible as a white powdery growth that forms on the surface of metal parts (see Figure 1, top right). Bubbling paint and deteriorating aluminum are telltale signs that metallic ions are being exchanged and degrading the surface of the metal.

Different metal combinations react differently to environmental influences, and a number of factors such as joining techniques, material properties, and surface roughness affect the chemical reactions occurring on rivets and the sheets they bind together. Hence, understanding the underlying electrochemistry is essential to developing robust corrosion protection.

Eager for faster testing and better protection methods, engineers at Helmholtz-Zentrum Geesthacht (HZG) and Daimler AG joined forces to investigate corrosion prevention using multiphysics simulation. HZG is a German institute focusing on materials, medical technology, and coastal research; Daimler AG is the manufacturer of the highly-revered Mercedes-Benz automobiles. The two

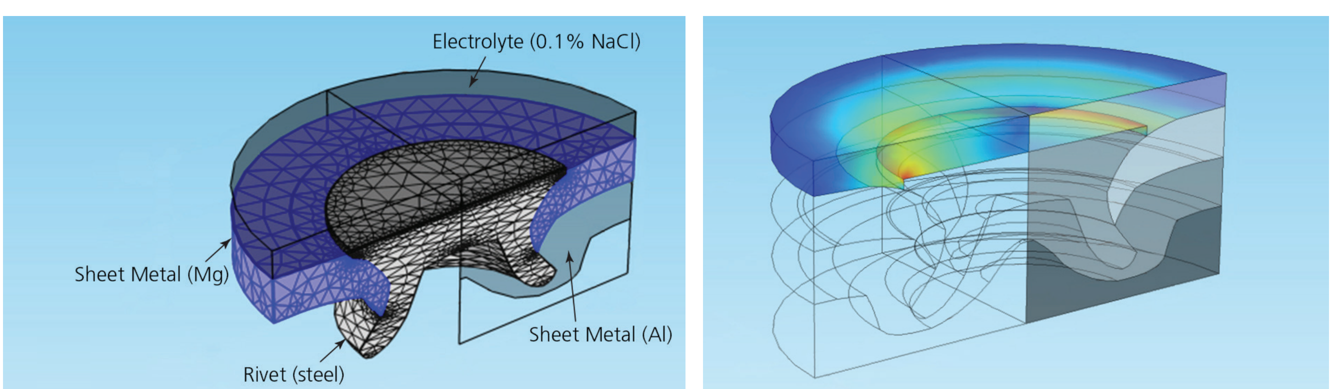

FIGURE 2. Left: Geometry depicting half of a punch rivet joint in COMSOL Multiphysics® software. Right: Simulation results show the current density at the surface of the rivet and sheet metal. The simulation mathematically models current flow at the rivet-sheet interface; the highest current density occurs at the sharp edge.

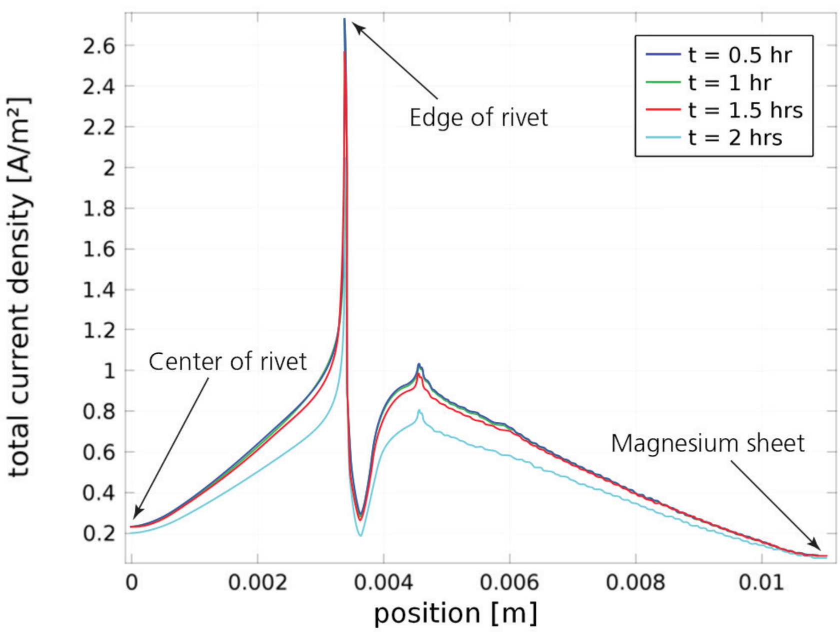

FIGURE 3. COMSOL® software plot showing the localized current density at different positions on the surface of the rivet joint.

teams sought ways to streamline rivet design and development, minimize physical testing, and reduce the need for subsequent steps such as surface treatment.

➔MULTIPHYSICS MODELING OFFERS INSIGHT INTO CORROSION KINETICS

To study galvanic corrosion kinetics, including material loss, surface conditions, and the long-term behavior of the interacting metals, Dr. Daniel Höche, scientist at HZG, created a simulation of a steel punch rivet joint using the COMSOL Multiphysics® software. The rivet is plated with an aluminum-zinc alloy that acts to cathodically protect the steel. The software allowed Höche to analyze the electrochemical interactions at the surface and edges of the rivet, predict the decay of the adjoined sheets, and adjust the geometry to minimize corrosion.

His model consists of the rivet, bonded metal sheets of aluminum and magnesium, a 0.1% NaCl electrolyte layer on the surface representing the outside environment, and a galvanic couple at the interface between the rivet and the sheets (see Figure 2). He also added a corner bur in the rivet geometry to simulate the presence of a sharp edge, which increases gradients in the electrolyte potential. This in turn increases current flow and hastens the electrochemical reactions that cause galvanic corrosion.

As the interface between the rivet and the sheets experiences corrosion, the magnesium sheet begins to degrade more rapidly than the other metals. The chemical reaction produces magnesium hydroxide ($Mg(OH)_2$) that forms a weak barrier film on the surface. Growth in this deposit layer actually increases resistance to further corrosion, hindering its own progress. A complete stop cannot be reached because of the porosity of the $Mg(OH)_2$, however, and the growth continues deeper into the metals.

In order to determine the electric current distribution and analyze the chemical response, Höche needed to account for this non-constant growth and the influencing material properties. Using the Chemical Reaction Engineering Module and Batteries & Fuel Cells Module, two add-ons to the COMSOL® software, he treated the rivet and the sheet metal like a set of electrodes. This allowed him to assess how the anode/cathode area ratio, the electrolyte exposure duration, and the changes in electric current due to $Mg(OH)_2$ buildup contributed to magnesium degradation.

"Since the porosity directly affects the barrier properties, the resulting surface topology is influenced by the downward degradation velocity and the opposing growth of the deposit. Basic galvanic current density computations

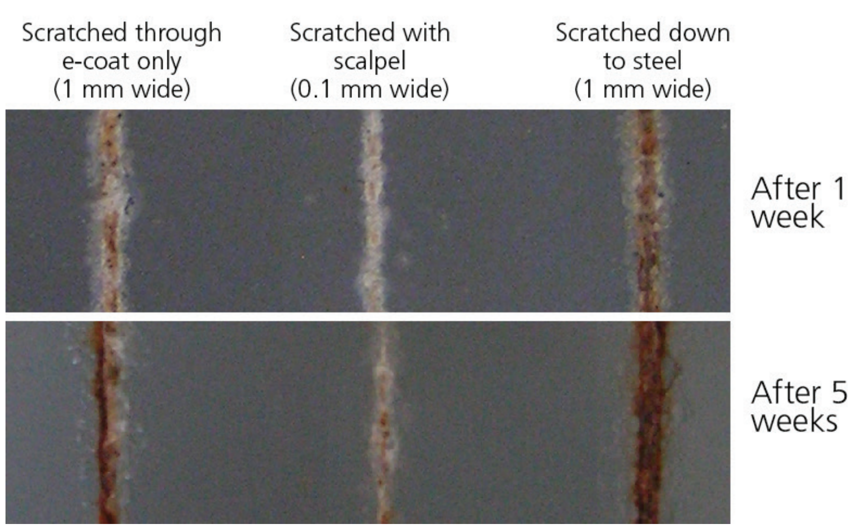

FIGURE 4. A corrosion test on a galvanized steel sheet showing visible corrosion in the scratched layers (view from above). Bösch created several initial scratches of varying depths and widths in order to analyze the influence of the scratch size on the delamination process. Results are shown after one week (top) and five weeks (bottom).

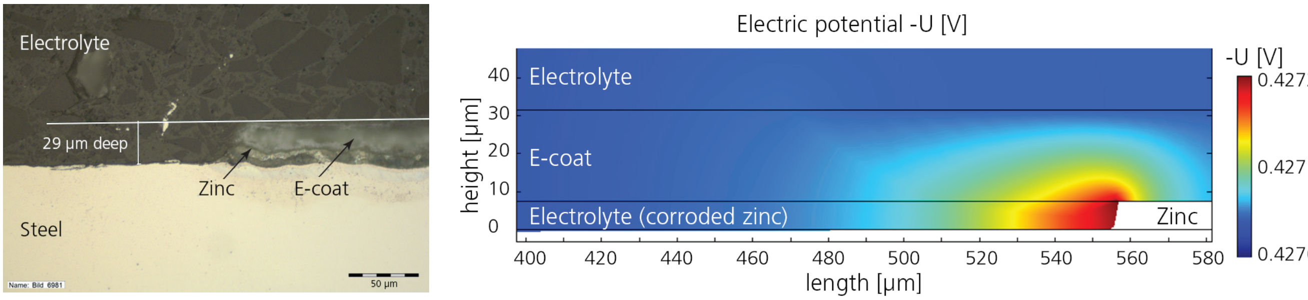

FIGURE 5. Left: Close-up of a cross-section of the test sheet where a scratch has destroyed part of the e-coat and zinc layers. Right: The COMSOL Multiphysics® software results showing the electric potential in the e-coat and electrolyte. The white region indicates the remaining zinc after much of it has already been consumed.

were modified by these layer growth aspects," Höche commented. "This led us to study time-dependent variations in the electrochemical response of the electrodes."

The model includes chemical reaction rates, known electrochemical properties of the metals, and a time-dependent function with an exposure period of 24 hours. His results report the electric potential and the current density when the rivet joint is exposed to the electrolyte, and reveal the surface coverage (the proportion of the sheets and rivet surfaces covered by $Mg(OH)_2$) at different times after immersion begins. The current density varies over distance from the center of the rivet, showing where corrosion will occur most rapidly (see Figure 3).

→DIGGING DEEPER: THE RISKS OF DELAMINATION

In addition to galvanic corrosion occurring at the rivet-sheet interface, other automotive components are in danger of being destroyed by the elements. Minor, seemingly superficial imperfections, such as a scratch in the coating or paint on a panel, open the door to corrosion and allow moisture and environmental electrolytes access to electrically conductive surfaces. In car paneling, small impairments can create a galvanic couple that causes delamination—the debonding of coatings on the metal sheets—which significantly weakens the corrosion protection.


Left: Dr. Daniel Höche, scientist at HZG.
Right: Nils Bösch, researcher at Daimler AG.

To analyze this additional risk, Höche worked with Nils Bösch, researcher at Daimler AG, to study delamination on a zinc-plated steel test sheet electrocoated with a layer of cathodic paint called an e-coat (see Figure 4). "Due to a scratch extending down to the steel surface, you can get a galvanic couple between the zinc and the steel and the zinc corrodes," explained Bösch. "This results in a crevice that grows continuously between the e-coat and the steel in the horizontal direction, rather than vertically through the layers." This behavior is quite similar to the process of crevice corrosion, which digs between two surfaces, creating fissures in the metal. Stress fractures at the base of these cracks can eventually cause part failure, even though the obvious damage and overall material loss may appear small.

Höche and Bösch used parametric sweeps in COMSOL to study the electric potential in the electrolyte and the e-coat for different e-coat barrier properties. Their model reported the corresponding horizontal growth of the crevice as it consumes the zinc (see Figure 5).

Their study to understand how the size of these surface defects impacts the rate of zinc consumption is ongoing. So far, the model indicates that the width of these defects has a greater influence than the depth: a smaller cathode/anode ratio and more limited diffusion is present in the narrower scratches, which slows the corrosion process compared to a wider impairment. The existing results are being used to further investigate coating flaws for their negative influence on corrosion protection.

→LAYING THE GROUNDWORK FOR LONGER-LASTING STRUCTURAL SUPPORT

Although corrosion is an omnipresent process that cannot be avoided entirely, it can be minimized through expert design and careful analysis. Höche and Bösch reduced the sharp edges in the rivet joint and honed the geometry to minimize the exposed area while maintaining mechanical stability. They also recommended an e-coat for the sheet metal that, based on the parametric study, would exhibit the lowest electric current and therefore the least decay in the paneling. Their COMSOL models offered indispensable insight into the relevant electrochemical behavior, providing the engineers at HZG and Daimler AG the tools for optimizing their rivet joints for the best corrosion defense.

"This kind of computer-aided analysis enhances the developments in lightweight design and enables identification of possible corrosion problems early in the design cycle," Höche concluded. "Despite the dangerous enemy that corrosion is to the automotive rivet, control of magnesium corrosion through knowledge-based processing and careful geometric design has come within our reach." ❖