

Corrosion Behavior of Mixed-Metal Joint of Magnesium to Mild Steel by Ultrasonic Spot Welding with and without Adhesives

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ABSTRACT

Development of reliable magnesium (Mg) to steel joining methods is one of the critical issues in broader applications of Mg in automotive body construction. Ultrasonic spot welding (USW) has been demonstrated successfully to join Mg to steel and to achieve strong joints. In this study, corrosion test of ultrasonic spot welds between 1.6 mm thick Mg AZ31B-H24 and 0.8 mm thick galvanized mild steel, without and with adhesive, was conducted. Adhesive used was a one-component, heat-cured epoxy material, and was applied between overlapped sheets before USW. Corrosion test was conducted with an automotive cyclic corrosion test, which includes cyclic exposures of dipping in the 0.5% sodium chloride (NaCl) bath, a constant humidity environment, and a drying period. Lap shear strength of the joints decreased with the cycles of corrosion exposure. Good joint strengths were retained at the end of 30-cycle test. Failure mode of joints without adhesive was Mg nugget pull-out, but was interfacial failure of samples with adhesive. Metal-metal bonding between Mg and steel was maintained throughout 30 cycles of corrosion exposure. Joint strength of corroded samples without adhesive decreased due to the erosion in the joint and in the parent material. For the samples with adhesive, the joint strength decreased due to the corrosion attack at the joint interface and the delamination of adhesive from Mg sheet. Adhesive was shown to help in minimizing the erosion of the interior surface of Mg sheet.

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INTRODUCTION

Magnesium (Mg) has great potential for use for weight reduction as it is the lightest structural metal known (78% lighter than steel, and 36% lighter than aluminum), has a high specific strength and superior damping capacity [1]. Moreover, Mg is one of the most abundant elements in the earth's crust and in seawater and can supply industry's needs for the foreseeable future. The ability to significantly increase Mg usage will help the auto industry meet future Federal Corporate Average Fuel Economy (CAFE) targets and reduce exposure to CAFE penalties. New regulations in 2016 require fleets to average 35.5 miles per gallon (MPG) up from about 27.3 MPG now. But the real challenge is to meet a proposal

that vehicles get 54.5 MPG in 2025. Weight reduction is one of the critical strategies to achieve the target. The rule of thumb is a 10% weight reduction improves fuel economy by 3%-4%. It can be more if the lighter vehicle needs a smaller engine, brakes and other components.[1] United States Automotive Materials Partnership (USAMP) has proposed to reduce the weight of an average North American vehicle (1,527 kg) by 132 kg by replacing 286 kg of current aluminum, iron and steel with Mg [2].

Two of the specific areas of concerns for broader use of Mg are reliable joining methods and corrosion. These two concerns are significantly magnified when dealing with Mg components attached to steel structures. Department of Energy (DOE) has been sponsoring projects to develop solid-

state joining technologies based on friction stir linear and spot welding (FSW/FSSW) and ultrasonic spot welding (USW) for joining Mg to steel. Both have been demonstrated to be feasible and successful [3,4,5,6,7]. However, a bigger challenge is the corrosion of mixed metal, i.e. galvanic corrosion because of the direct metal contact between Mg and steel.

In a previous study [8,9], corrosion tests were conducted on USW between Mg and steel. The test was conducted with an automotive cyclic corrosion test, which includes cyclic exposures of dipping in the 5% salt bath, air drying, then a constant humidity environment. It was expected that the galvanic corrosion could be very severe and the results confirmed it. However, surprisingly the major failure mode was not the direct erosion of the metals, but rather a combination of the excessive growth of magnesium hydroxide $Mg(OH)_2$ and the mechanical deformation by the thickening of $Mg(OH)_2$ in the crevice between Mg and steel sheets to weaken and eventually separate the joints.

An adhesive layer is added in this study to examine its effect to the strength of joints and protection from corrosion. The galvanic corrosion has four basic requirements to occur: an anode (e.g. magnesium), direct electrical contact, a cathode (e.g. steel), and presence of electrolyte (e.g. winter road salt) at the interface between anode and cathode. It is assumed that the addition of adhesive can block the access of electrolyte to the joint interface to protect the joint from corrosion. At the same time, before the corrosion study, the feasibility of applying adhesive with USW will have to be proven.

Adhesive has been used in conjunction with resistance spot welding, called ‘weldbonding’ [10] in automotive body construction, to provide benefits of higher stiffness and prolonged fatigue life. The same concept was applied to friction stir spot welding (FSSW) (or spot friction welding (SFW)) with adhesive, called “spot friction weldbonding” by Pan, et al [11]. Therefore, there are two objectives in this study: the first is to produce USW joint with adhesive (“ultrasonic spot weldbonding”), the second is to study the corrosion effect of such joints. A salt solution of 0.5% is used instead of 5% as in previous study for better reflecting of the current trend of automotive corrosion test requirements. [12]

EXPERIMENT

Two sets of USW samples were made: without and with adhesive. Mg and steel materials, machine, and fixture used to make ultrasonic-welded lap-shear samples were identical as described in [3,4,6,7,8]. The materials used for these experiments were sheets of 0.8-mm-thick hot-dip-galvanized mild steel and 1.6-mm thick AZ31B-H24. Prior to welding, the surfaces of the AZ31B sheet were buffed with nonmetallic abrasive pads (Scotch-Brite™) to remove surface oxides and produce shiny surfaces. Both metals were cleaned with acetone followed by isopropyl alcohol to remove lubricants and surface debris. Adhesive material is a one-part

heat-curing epoxy adhesive, Betamate 73305, from Dow Automotive [13]. The adhesive was specifically designed for weldbonding of steel and aluminum, but was advised to be suitable for Mg [14].

The machine used for the ultrasonic spot welding was a single-transducer wedge-reed Sonobond CLF 2500. The coupons used for welding the lap-shear test specimens had dimensions of 100 mm × 30 mm, and they were overlapped a distance of 40 mm in a fixture. The welds were centered in the overlap region. The size of the overlap and the process parameters were selected for optimal joint strength without adhesive. Spot welding was done using a power of 1500 W at impedance setting 8 and welding time of 2.1 sec. The only clamping in the present experiments was the pressure applied by the welding (sonotrode) tip. Specimens were positioned for welding so that the primary vibration direction of the sonotrode was perpendicular to their long axis. The sonotrode tip was made from T1 steel, and it had a flat, rectangular face of 7 mm × 7 mm [4]. The line pressure to the tip clamping mechanism was adjusted to make the welds under constant nominal pressure of 39 MPa.

Samples with adhesive were made in a process similar to the weldbonding process of resistance spot welding (RSW), i.e. a paste adhesive is normally applied to one sheet, the joint is closed, then spot weld is made through the adhesive. A masking tape was first put on both the Mg and steel surface to mask out the areas not be applied with adhesive. An X-shape bead of adhesive was applied on the steel surface with added 0.3 mm Zirconia beads as spacers. The steel sheet was then overlapped with the Mg sheet, as shown in Figure 1. The assembly was transferred to the USW fixture for welding. The welded samples were then cured in a furnace at 165°C for 30 min. The masking tapes were peeled off before the samples were subject to the corrosion test.

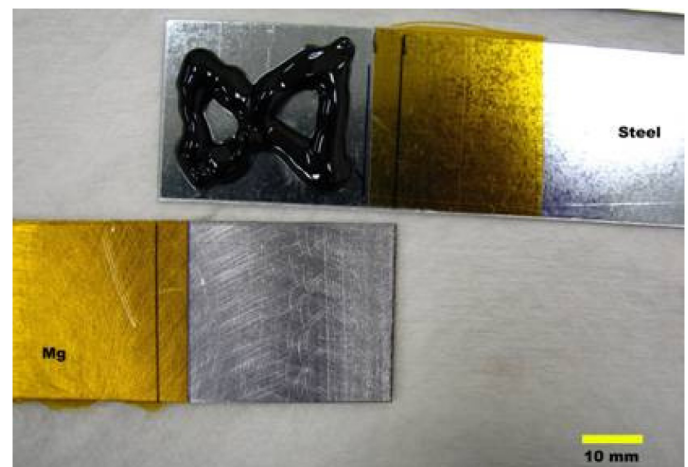


Figure 1. Dispensing of adhesive on the steel sheet before overlapped with Mg sheet. Steel and Mg sheets were masked by tapes (yellow).

An automotive corrosion cycle test, Ford Accelerated Cyclic Corrosion Test L-467, was applied. The cycle consists of immersion or constant spray of 0.5% NaCl solution for 15 minutes, followed by a humidity exposure at 25°C and 95% relative humidity for 5 hours and 45 minutes, and finally a drying period at 50°C and 70% relative humidity for 18 hours. The whole cycle takes 24 hours. Humidity chambers were set according to ASTM E104-02 [15]. A complete set of test lasts for 30 cycles. A major difference from the test conditions in previous study [7,8] was the 5% of NaCl solution specified in Ford Arizona Proving Ground Equivalent Corrosion Cycle (APGE) and the temperatures and times in the humidity and drying periods.

One joint sample was pulled from the test at the end of each cycle for mechanical testing of tensile lap-shear setup. In addition, one sample was pulled every 5th cycle for metallographic examination. A total of 36 samples were used at the beginning of the test. Both non-corroded and corrosion-tested samples were cross-sectioned and examined by optical microscope, scanning electron microscope (SEM) and energy dispersive spectrometer (EDS). Mechanical test was conducted on an Instron machine at a crosshead speed of 10 mm/min without spacer added to offset the centerline.

RESULTS AND DISCUSSIONS

Strength of Joints

Ultrasonic spot weldbonding was successful in making test samples for the study. The results of the lap-shear failure load vs. the cycles of corrosion exposure of samples without and with adhesive are presented in Figure 2. The average failure loads of non-corroded samples without and with adhesive are 4.1 and 6.4 kN, respectively, marked as the horizontal dash lines. These values are to compare to the failure loads of samples exposed to the corrosion cycles. Failure loads of corroded samples decrease with each cycle of exposure, in general. All of the samples, both without and with adhesives, maintained useful strength after 30 cycles of corrosion exposure. Samples without adhesive kept about 70% of the strength at end of the 30 cycles compared to that of noncorroded samples without adhesive. Samples with adhesive maintained about 45% of the strength from corresponding non-corrode samples with adhesive. These are great departures from the previous study [8,9] which showed the corroded samples lost almost all the strength after 17 cycles of corrosion exposure to the APGE test protocol. This may be contributed from the major difference in the test methods: 0.5% NaCl solution used in the current L-467 test procedure vs. 5% NaCl used in the APGE.

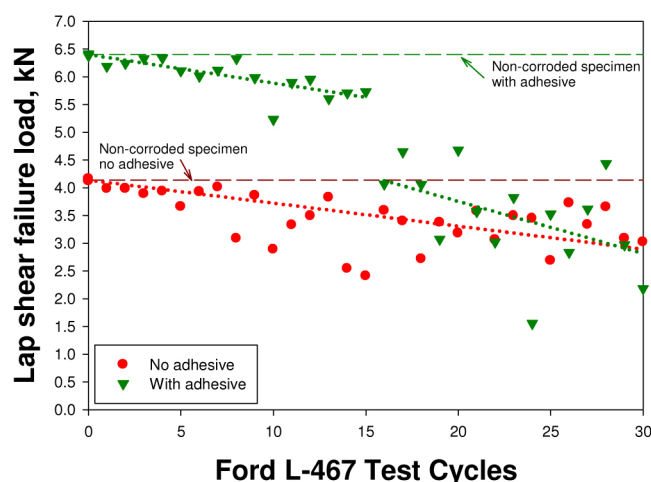


Figure 2. Lap shear failure loads of USW with and without adhesive vs. cycles of corrosion exposure. Two dash-lines indicate the failure loads of non-corroded samples.

Although only one sample was mechanically tested per corrosion cycle, the decrease of strength of samples without adhesive falls linearly with the number of corrosion cycles. However, for the samples with adhesive, the relationship between strength and corrosion cycles follows two separate trends: one is from beginning to the 15th cycle, the second is from the 15th cycle to the end of 30th cycle. Further examination reveals different failure modes which provide the reasons of these trends.

Failure Mode of Samples without Adhesive

Failure modes from samples after tensile lap-sheared test reveal various mechanisms which can help in explaining the differences of the relationship between strength and corrosion cycles. Figures 3(a) and (b) are the matching (inner) surfaces of the AZ31 and steel sheets from a tensile lap-sheared sample without adhesive before corrosion test. It shows a “nugget pull” failure mechanism with a piece of Mg, about the same size of the welding tip (7 mm × 7mm), left on the steel surface. It clearly indicates a good bonding [4] between the Mg and steel which is stronger than the strength of Mg parent material.

The failure mode of nugget pull-out is consistent through the cycles of corrosion exposure for majority of the samples (26 samples out of 30 tested). As an example, Figures 4 (a) and (b) are the matching (inner) surfaces of the AZ31 and steel sheets from a tensile lap-sheared sample after 28 cycles of corrosion exposure. A piece of Mg nugget is shown on the steel surface, although it is significantly smaller than the one shown in Figure 3(b). The lower strength of the joint can be expected from the smaller nugget since the strength of the spot weld is related to the diameter of the nugget [16]. The white substance on the Mg sheet was identified to be Mg(OH)₂ compound by X-ray diffraction [8,9] which is in