PROTECTION of AUTOMOTIVE Mg ALLOYS for AUTOMOTIVE STRUCTURAL APPLICATIONS

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Increasing green house gas concerns have prompted automakers worldwide to use lighter materials in cars of various sizes and models. Mg alloys, with the highest strength-to-weight ratio of the common engineering alloys, have been used in castings of various components. The forecast trend for the use of the metal in automobiles suggests a more rapid growth pace in the coming decade.

However, Mg alloys happen to be among the most reactive materials in natural environments, such as those applicable to exterior automotive conditions. While the general corrosion rate of Mg alloys can be reduced to quite an acceptable range by controlling the levels of impurity elements, the most challenging form of corrosion is galvanic corrosion: the corrosion of Mg parts when in contact with other materials such as coated steel bolts and nuts. Other forms of corrosion damages such as pitting corrosion and stress corrosion can also be issues of concern for design engineers.

In the research work that is undertaken at the Materials Technology Laboratory of Natural Resources Canada in partnership with a major USAMP (US DOE) program, an effort was made to select environmentally friendly coatings for Mg alloys and to evaluate new coatings for steel fasteners and new alloys for use as washers and spacers. The results of laboratory tests, both salt spray testing and electrochemical measurements, are presented in this paper; opportunities for development of new materials in this area are also explored.

I INTRODUCTION

1.1 General background

Manchester has been an important landmark in the development of magnesium as a commercial material. In 1860, when UMIST was still known as the Mechanics Institute, Mg was produced here by Johnson Matthey & Co using the Deville-Caron process. In those days, the metal was mostly used for photographic purposes. Mg-based alloys are now used in many applications, including as structural materials owing to their high strength-to-weight ratio.

The use of Mg in automotives started in the 1930s [1], when cast Mg lower crankcases were put on city buses in London, England. The first significant large-quantity use of Mg alloys began with the production of rear-engined VW Beatles in Germany in the 1930s, in which the Mg crankcase and transmission housing castings in each vehicle weighed as much as 17 Kg. Now Mg components can be found in many models of automobiles made by various car-makers around the world. In the past few years, several new applications in various parts of passenger vehicles have been developed, including an oil pan in certain Honda models, a gearbox housing in the VW Passat and a radiator support assembly in the 2003 new models of Ford F150 truck [2].

The main technical reasons why Mg alloys have not been used more widely in the average vehicle are their propensity to creep and their low resistance to corrosion. While the creep properties can be improved considerably through alloy chemistry design, effective mitigation of corrosion problem relies on protective coatings and on the use of galvanically compatible materials for the joining areas where Mg is in contact with other surfaces.

In terms of general corrosion rates, modern Mg alloys, in which the level of impurity is strictly controlled, can perform quite satisfactorily in general atmospheric conditions. For example, in the study by Hillis et al [3] using exposure panels on the gulf coast, the measured corrosion rate of AZ91D was less than 4 micrometers per year. In this type of alloys, the harmful impurity elements are Ni, Fe and Cu, as the presence of these elements provides effective cathodic sites for hydrogen evolution. The high purity grade of AZ91 (the D series) has less than 20 ppm Ni, less than 50 ppm Fe and less than 300 ppm Cu. The common alloying elements, Si and Zn, in the Mg alloys do not change the corrosion resistance to any significant extent. Mg castings of appropriate compositions used in the automotive interior condition tend to resist well general corrosion.

The difficult application cases are for those components that will be subject to abrasive and impinging actions of the road sand, salt and slurry, a typical road condition for cold climate countries such as Canada. Under these conditions, not only the general and pitting corrosion rates of bare Mg alloys will be high, but also the effects of galvanic corrosion of the coated fasteners will be much stronger as the protective coating on the steel fasteners will deteriorate faster under the influence of the road salt.

The galvanic current may be expressed by the equation [4]:

$$I = \frac{E_K - E_A}{R_K + R_A + R_E + R_M}$$

where E_A and E_K are the anodic and cathodic open circuit potentials, respectively; R_A and R_K are the anodic and cathodic polarization resistance, respectively; R_E is the electrolyte resistance and R_M is the metal resistance.

Since R_K and R_E are much smaller than R_A and R_M, this equation can be further simplified as:

$$I = \frac{E_K - E_A}{R_K + R_E}$$

To limit galvanic corrosion, the difference between the corrosion potentials of the contacting metals must be small and the polarization resistance must be as high as possible. A proper design of the joining mechanism is necessary to avoid the small-anode-and-large cathode combination, but with the limitation of space allowance in a real automotive part, the practical approach is to select the most compatible material at an acceptable cost.

1.2 The corrosion and protection aspects of the Structural Cast Magnesium Development (SCMD) project

Under the joint sponsorship of the USAMP (US DOE) SCMD project [5] and the Canadian Lightweight Materials Research Initiative (CLIMRI) a research project was initiated at the Materials Technology Laboratories (MTL) of CANMET to identify and investigate cost-effective measures for protecting magnesium alloys used as structural components such as an engine cradle. The specific aspects of the overall project that are related to corrosion research are:

(A) To study the corrosion and wear properties of commercial and novel coating systems of magnesium;
(B) To assess the protection properties of various relevant coating materials for fasteners, washers and spacers materials that will be in contact with Mg surfaces, and
(C) To evaluate the susceptibility of Mg to SCC and corrosion fatigue in a typical structural application.

In the course of the project, seventeen different types of Mg coatings have been collected from industrial suppliers. These coatings were subject to ASTM B117 salt-spray testing for 1000 hours and the top-performing coatings were subsequently selected for further evaluation.

The overall test plan consists of the following steps: I) Salt-spray screening testing; II) microscopic characterization of selected coating systems, III) Galvanic corrosion testing of fastened Mg plates in both bare and coated conditions, IV) Erosion corrosion testing of coated Mg samples, V) SCC testing of selected Mg alloys, and VI) field on-vehicle testing of final candidate coating systems.

In Step III, to evaluate the resistance of the Mg coating against galvanic corrosion when the Mg plated is fastened with steel bolts and nuts, several types of ‘promising’ fastener coatings were selected based on a thorough literature survey, and these fastener coatings were subject to the GM 9540P cyclic salt spray test. While the entire test program is not yet completed, preliminary test results showed encouraging indications of the top-ranking coating systems for further field test, which will be carried out using the prototype cast Mg cradles.

An additional in-house research effort was also made to develop novel materials for use as washer and spacers that can reduce the effects of galvanic corrosion between the bolt head/nut and the coated magnesium surface. Considering that a washer or a spacer is the intermediate material between the cathode and the anode of the galvanic corrosion cell of the fastener/Mg alloy assembly, a cost-effective material for this use can be of interest to the manufacturers of Mg components. The test results of these new materials are also included in the sections below.

II SELECTION AND EVALUATION OF ADVANCED COATING SYSTEM FOR MG ALLOYS

2.1 Coating selection

Extensive research and development effort has been made in the past 60 years or so to coat Mg components with a protective surface barrier. A recent review by Luan [6], as part of the CLIMRI Mg Corrosion Project, provided a comprehensive coverage of the various coating systems and their application techniques for Mg alloys. To be useful for automotive applications the coating process must be adaptable for the well established automotive manufacturing processes, and it must be cost-competitive and effective.

Chromate conversion coatings were widely used for Mg alloys used in aggressive conditions. However, the environmental and health concerns of these coatings have prompted the industry to look for alternative user-friendly coatings. The selection of a protection coating for magnesium alloy components needs also take into consideration the effects of the coating materials on the eventual recycling of the component [7]. Pigments in organic coatings can introduce oxides of Cu, Ti, Cr, Fe, Sb, Ni, Si and Al in the post-consumer scrap. Other pigments may include Cl, F, Co, Mn and P. Electroless nickel coatings, for example, can be a source of significant Ni contamination as well as minor P or B contamination in the recycled metal.

Based on the above consideration and the product availability, a total of seventeen different types of coatings were selected for this study. Essentially these fall into four groups:

Group A: Anodizing coating – Tagnite, Keronite, Anomag, Tagnite with Ecoat, Tagnite with Ecoat
Group B: ADSIL AD series (four types), Sol Gel Ver.1, Sol Gel Ver.2,
Group C: Alodine 5200 with powdercoat, HLF-686& HLF-815
Group D: Polyurea, Al-Li embedded polymer coating, Ship-to-shore

2.2 Coating evaluation as per ASTM B117 test standard

The ASTM B117 test standard was used as a screening test for the coated and uncoated Mg samples. For this test, the salt solution used is prepared by dissolving 5 parts sodium chloride into 95 parts water (conforming to Type IV in ASTM specification D1193). The pH of the salt solution was set to be in the range of 6.5 – 7.2. The temperature of the chamber was set at 35 °C, and was measured twice a day at an interval of at least 7 hours.

The samples are first cleaned in dry ethanol to remove any contaminations resulting from handling. They are then placed within in a plastic rack at an angle between 15° and 30° from the vertical line and separated sufficiently from one another so that dripping from one sample does not affect any adjacent samples. Series of samples were tested for various durations, namely, 200, 400, 600, 800, and 1000 hours of testing.

Figure 1 shows a typical setup of the coated test samples. Visual examination of the test plates was performed at preset intervals. In the case of the scribed samples, the creeping or lateral expansion of corrosion from the scribe lines and degree of disbondment underneath the coating were the criteria for assessing the performance of a coating. The scribed sample were typically tested for 240 hours.

Figure 2 shows two examples of the scribed test samples after 240 hours of testing. The sample treated with Alodine 5200 then coated with a powder coat did not show any visible creeping of corrosion damage from the scribe line, whereas the sample coated with polyurea had some corrosion underneath the coating, which indicates that this coating alone is not sufficient for protecting Mg under severe salt conditions.

Based on the ranking of the test samples after 1000 hours testing, the top candidate coatings were selected for further evaluation. These coating systems are:

1) Alodine 5200 with epoxy powder coat
2) Tagnite anodizing with epoxy topcoat
3) Anomag anodizing with Ecoat
4) Polyurea topcoat

Alodine 5200 [8] is an organometallic titanium based primer which is used as a chromate-replacement conversion coating for light metals. This primer is usually followed with one or more topcoats. For this work, an epoxy powder coat was used as the topcoat.

Tagnite [9] is a Cr-free equivalent of the Dow 17 and HAE anodizing coating. It is based on the formation of a hard, tightly packed magnesium oxide growing from the Mg base. The coating consists mostly of a hard magnesium oxide with minor surface deposition of fused silicates.

Anomag [10] is another anodizing coating for magnesium. The protective alkaline phosphate layer can be made to various thickness. In this work the typical thickness is about 10 to 15 micrometer.

Polyurea [11] is a fast-curing polymer resulting from the reaction of an isocyanate prepolymer and a blend of primary and secondary amines. For this work, the coating thickness varied from 200 to 500 micrometers. The use of this product for this project is based on its good elasticity and adhesion to an epoxy-type topcoat. Although not seen as an adequate coating for protecting Mg alloy by itself, the special advantage of this coating is that it can resist chipping and impact damage of the road sand and gravels when used as a topcoat.

III GALVANIC CORROSION TESTING AND EVALUATION

3.1 Test method

A GM test procedure, GM9540P, was chosen as the method for evaluating the galvanic corrosion susceptibility of Mg (coated and uncoated) fastened with M8 and M10 fasteners.

A Singleton CCT-10C cyclic corrosion chamber was used for this test. The GM9540P testing cycle is comprised of four salt mist applications to the tested materials at regular intervals during the first 8 hours, followed by 8 hours of humidity cabinet exposure at 100% RH, and 8 hours of dry-off period at 30% RH and at 60 C. The salt solution used consisted of 0.9% sodium chloride, 0.1 % calcium chloride, 0.25% sodium bicarbonate dissolved into water per ASTM Type II Reagent Grade specification. The pH of the solution was within the range of 6-9 as outlined in the test standard. The test conditions are known to be less severe than those of the ASTM B117 test method.

3.2 Design of test plates and materials selection

The test plates of AM60 measuring 4”x 6.25”x 0.10” were drilled to allow five fastener units: three M8 units and two M10 units. Each fastening unit consists of one bolt (M8 or M10), two washers and a hex nut. The dimensions and the layout of the test plate are indicated in Figure 3.

Selection of appropriate fastener coatings was one of the key steps in this work. Zinc-coated fasteners are widely used in the automotive industry. However, typical zinc coatings are passivated using a sealing chromate conversion coating. This coating contains a mixture of trivalent and hexavalent chromium compounds. Some of the hexavalent chromium compounds are more soluble than their trivalent ones, and are capable of leaching to the metal surface upon scratching, so that the chromate protection will be renewed in this area. Thus, chromates are said to have self-healing properties. Iridescent or yellow chromates contain much more hexavalent chromium than the blue chromates, and thus have much better self-healing properties. Unfortunately these well developed fastener coating systems are being phased out by car-makers in North America and elsewhere due to the health problems associated with hexavalent chromium compounds.

Among the common Cr(VI)-free coatings, Sn-Zn [12] and Zn-Al coatings are the well known types. Al-Mg coating by an electroplating process [13] is a new development specially for those applications involving contact with Mg alloys. These three coatings were evaluated in the first phase of the testing program.

The Sn-Zn coating selected for this work was produced by electroplating and has about 75% Sn and 25% Zn. This coating is currently widely used in the applications where electrical conductivity between the joining members is to be maintained. The minimum coating thickness in the fasteners selected in this work is about 8 micrometers.

The Zn-Al duplex coating consists of an inner layer of Zn powders in an inorganic binder and a top organic barrier coat embedded with Al flakes. The zinc-rich (up to 95% zinc) inner layer provides sacrificial protection, and a study [14] has shown that this cathodic protection capacity on the base steel is reduced when Al content was higher than 20%. In this study, the Al content in the duplex Zn-Al coating selected ranges from 5 to 10%.

The Al-Mg coating was developed by Reinhold et al. [13]. The electrolytic deposition process and corrosion behavior of aluminum-magnesium alloy coatings were also discussed in a paper by Reinhold et al. [15]. The aluminum-magnesium coatings were deposited by a three-electrode deposition process in which Al and Mg anodes provide the independent source of the metals for co-deposition. The magnesium content can be varied from 5 to 50% by weight in a uniform coating. However, when magnesium content was more than 40% by weight, the passivity was reduced and coating was non-homogeneity, and the anodic dissolution cannot be avoided. X-ray diffraction tests also showed that the corrosion resistant phase $Al_{12}Mg_{17}$ are stable at magnesium content between 15 to 25% by weight. It was intended that some of these coatings would be included in the test matrix for this work, but the shortage of sample supply caused the testing to be delayed till a later time.

In addition to the coated steel fastening units (bolts and nuts), some special fasteners were also tested for various technical and scientific reasons. These include a Ti-6Al-4V bolt and nut, and a RIBE high-strength Al TORX bolt [16]. The overall test parameters are summarized in Tables 1 and 2. The selection of washer materials and their coatings was based on the current industry recommendations and published performance data [17,18].

A number of in-house made prototype washers based on Al-Mg chemistries were also evaluated. In these chemistries, the main elements are Al (75-85%) and Mg (25-15%) plus some micro-alloying additions. The three chemistries are referred to as Exp2089, Exp2090 and Exp2091. Washers of sizes fitting the M10 and M8 bolts were made from permanent mold cast plates.

3.3 Test results

Figures 4a and 4b show the appearance of the fastened uncoated AM60 plate before the start of the GM9540P test; Figures 5a and 5b show the appearance after 5 cycles of testing and Figures 6a and 6b after 23 cycles.

The effects of washers on the galvanic corrosion of Mg are demonstrated very clearly in Figures 5a and 5b. The fastener unit which did not contain a washer, Unit A, showed formation of visible corrosion product around the bolt head after as little as five cycles of testing. The back side of the same bolt, where a Exp2091 washer was used (Figure 5b), showed essentially no sign of galvanic corrosion. Corrosion in the vicinity of other fastener units, which all included washers in their assemblies, was light and quite uniform throughout the entire surface. The effects of washers are even more drastic after testing for 23 cycles, Figure 6a and 6b. Although both sides of the Mg plate started to show considerable accumulation of corrosion product, the build-up of corrosion product around Unit A, where no washer is used, became massive.

The Ti bolt and nut and washers remain intact, as would be expected. However, a ring of corrosion product started to show up immediately adjacent to the Ti washer. All the other washers, namely the anodized Exp2091 washer, the anodized 'import' 6061 and Exp2091 showed little effects of galvanic corrosion on their respective surrounding areas. General corrosion on the Mg plate seemed to be heavier in the bottom half of the plate than in the top half of the plate, reflecting the greater amount of salt and water deposition towards the bottom side of the four-inch wide plate.

The other series of galvanic corrosion testing was on a AM60 plate coated with an Alodine 5200 plus a powder coat. Figure 7 shows the appearance the plate right after assembly and Figure 8 after 18 cycles of testing. In comparison to the bare AM60 plate, the performance of a coated Mg AM60 plate fastened with various combination of fastening units showed no visible evidence of corrosion on the Mg plate or the washers after 18 cycles of testing. There were a few spots of red-rust emerging on the Zn-Sn coating on the bolt head itself, likely due to damage during the application of the torque loading.

The two series of galvanic corrosion testing showed conclusively that: 1) A good coating ssytem on the Mg alloy can significantly mitigate galvanic corrosion of Mg when in contact with coated steel fasteners; 2) Use of appropriate washers can drastically reduce the extent of galvanic corrosion on bare Mg alloys even when they are used in uncoated conditions.

4. ELECTROCHEMICAL MEASUREMENTS ON AM60 ALLOY AND THE EXPERIMENTAL AL-MG ALLOYS

4.1 Test setup

Open-circuit potential and linear polarization resistance(LPR) measurements were carried out using a Solatron 1287 system controlled with a Corrware software. The cell used was an EG&G three-electrode configuration and the test was done at ambient temperature. The solution consisted of a 1 M NaCl solution with the pH adjusted to 11 by adding appropriate amount of 0.1 M NaOH solution.

The tests started with a measurement of the open circuit potential (OCP) for 40 minutes. After an OCP was established, a linear polarization resistance measurement in a potentiodynamic mode at a scan rate of 1 mV/sec was initiated. The scan range was from

10 mV below (more cathodic) of the OCP up to 10 mV above the OCP. Upon a successful LPR measurement, a larger polarization curve was obtained for a range that extended from 400 mV below to 400 mV above the measured OCP using the same scan rate.

4.2 Test results

Figure 9 shows the polarization curves for Al alloy 6061, Mg alloy AM60 and the three experimental alloys. AM60 showed a corrosion potential of –1.5 V(SCE) and the 6061 sample showed a potential of about –1.2 V (SCE). The three experimental Al-Mg alloys (#2089, #2091 and #2089) all showed a corrosion potential in the vicinity of that of AM60 alloy. As the galvanic corrosion is driven by the difference in the corrosion potential of the two coupling metals, it is conceivable that the galvanic current flow between Mg alloys and the new Al-Mg alloys will be small.

The more interesting feature of this comparison is that in more anodic potential ranges, the behaviour of the new Al-Mg alloys is very similar to that of AA 6061. This means that the long-term corrosion rates of the new alloys should be very comparable to AA6061.

Table 3 shows the LPR data for AM60, AA 6061 and the three new alloys; the corrosion resistance of AM60 in 1 M NaCl solution is about 170 Ohms*cm^2 and AA6061 alloy had a resistance of 23,000 Ohms*cm^2. Two of the three new alloys had a resistance slightly greater than that of AA 6061 but they are generally in the same range. These LPR data predicts a good general corrosion resistance of these new alloys in salt-laden atmospheric conditions. To further validate this point, long-term salt-spray testing was done on these materials, as shown in the section below.

V CYCLIC SALT SPRAY TESTING ON THE NEW Al-Mg ALLOYS IN COMPARISON WITH AM60 AND AJ62LX

In order to evaluate the long-term corrosion property of the new Al-Mg alloys, cyclic salt-spray testing of AM60, AJ62LX, Exp 2089 and Exp2091 samples was carried out using GM9540P test method. Figure 10 shows the appearance of the test panels after 25 cycles of testing. The weight change, in terms of gram per square centimeters of the sample surface, is shown in Figure 11. The AM60 and the new AJ62LX alloy, made by Noranda, were included to serve as the performance “baseline”. While the two commercial Mg alloys showed comparable weight losses over the 25 cycle period, the new Al-Mg alloys (Exp2089 and 2091) showed some weight-gain, likely as a result of the build-up of Al oxide on the sample surface. Al oxide was not easily dissolved in the acid solution used for cleaning of Mg alloys.

SEM examination of the Sample Exp2091 after 40 cycles of testing showed that there is uniform coverage of a protective corrosion product on top of the Al-Mg base metal, as can be seen in Figure 12. EDS analysis, Figure 13, indicated that the surface film is rich in Al, oxygen and Mg, indicative of an Al-rich oxide.

VI SUMMARY AND CONCLUSIONS

The USAMP-CLIMRI joint project on Mg corrosion and protection is continuing at the time of this special symposium. Some of the tasks, including the field testing of selected Mg/fastener coating systems and SCC testing of selected Mg alloys, will be completed over the next year. Initial results from completed tasks, however, are encouraging for the future wide-scale application of Mg alloys as structural components in automobiles. Specifically, the following conclusions can be drawn at this stage:

1) There are commercially available costing systems for Mg alloys that can satisfy aggressive testing conditions established by the industry. For example, the chromate-free conversion coating with an epoxy powder coat selected for this study is one of them. This coating system has demonstrated effective protection against galvanic corrosion in the testing conditions applied.

2) Galvanic corrosion between fasteners and Mg alloys can be effectively mitigated though the use of appropriate types of washers. In this work, washers made of AA 6061, anodized 6061, as well as the newly developed prototype Al-Mg alloys, can all produce similar effects.

3) The in-house developed Al-Mg alloys have corrosion potentials that are very close to that of the AM60 alloy, indicating a low electrochemical driving force for galvanic corrosion between them. Long-term cyclic exposure testing has also shown that the new materials have good corrosion resistance in salt-laden environments.

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Table 1. Test parameters for galvanic corrosion testing on a bare AM60 plate

Fastening Unit	Bolt/coating	Nut	Washer on the front side	Washer on the backside	Note
A	M10 with duplex Zn-rich coating	M10 with duplex Zn-rich coating	none	EXP2091	
B	M10 with duplex Zn-rich coating	M10 with duplex Zn-rich coating	Anodized EXP2090	EXP2091	
C	M8 RIBE bolt	Ti –6Al-4V	6061	Anodized EXP2091	
D	Ti –6Al-4V	Ti –6Al-4V	Ti –6Al-4V	Ti –6Al-4V	
E	M8 with duplex Zn-rich coating	M8 with duplex Zn-rich coating	Anodized 'Import' 6061	Anodized 'Import' 6061	

Table 2. Test parameters for galvanic corrosion testing on a AM60 plate coated with an Alodine5200 plus a powder coat.

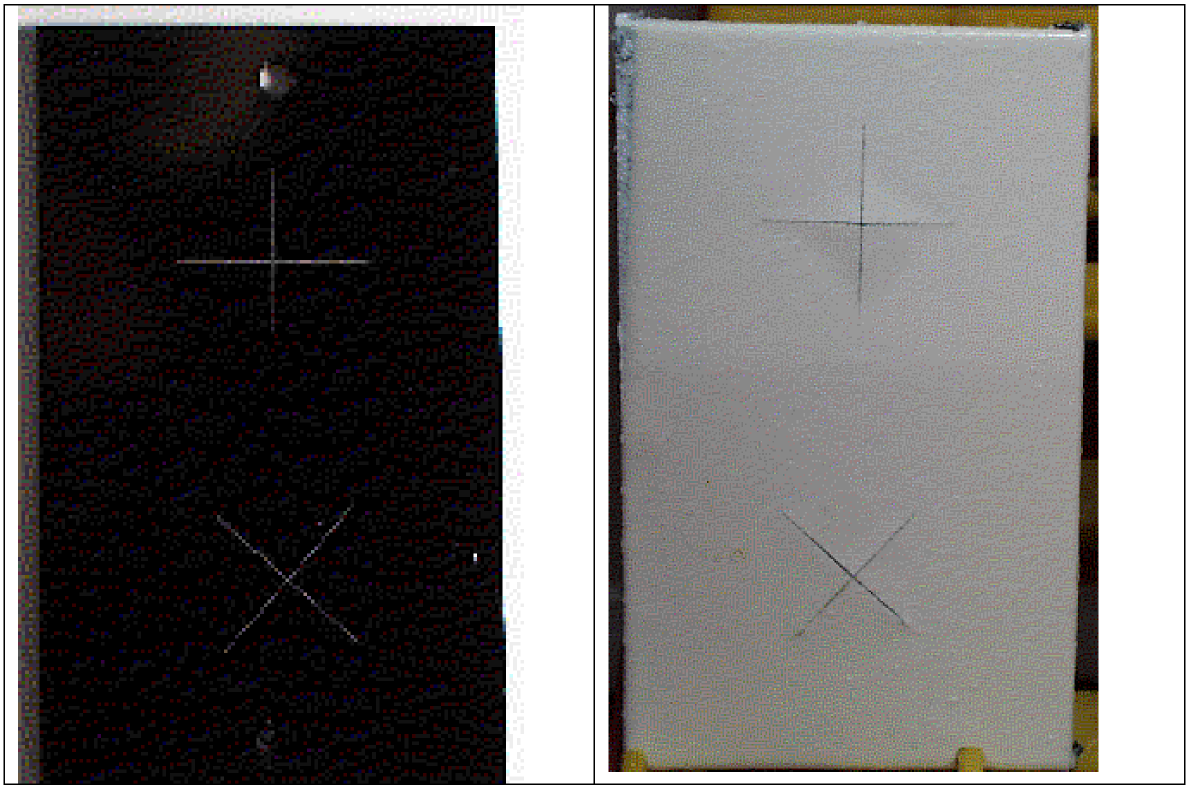
Fastening Unit	Bolt/coating	Nut	Washer on the front side	Washer on the backside	Note
A	M10 with Sn-Zn plating	M10 with duplex Zn-rich coating	none	6061	The finishing on bolt and nut is black
B	M10 with duplex Zn-rich coating	M10 with duplex Zn-rich coating	6061	EXP2091	
C	M8 with duplex Zn-rich coating	M8 with duplex Zn-rich coating	Anodized 6061	6061	
D	Ti –6Al-4V	Ti –6Al-4V	Ti –6Al-4V	Ti –6Al-4V	
E	M8 with duplex Zn-rich coating	M8 with duplex Zn-rich coating	EXP2091	Anodized 'Import' 6061	

Table 3 LPR test results for AA6061, AM60 and the three experimental alloys

Al6061	23151
N2089	16145
N2090	27901
N2091	31263
AM60	170

(Soln: 1 M NaClRp, Resistance in Ohms)

Figure 1 Appearance of coated Mg AM60 plates during ASTM B117 testing



(a) (b)

Figure 2 Appearance of scribed coating samples after 240 hr.

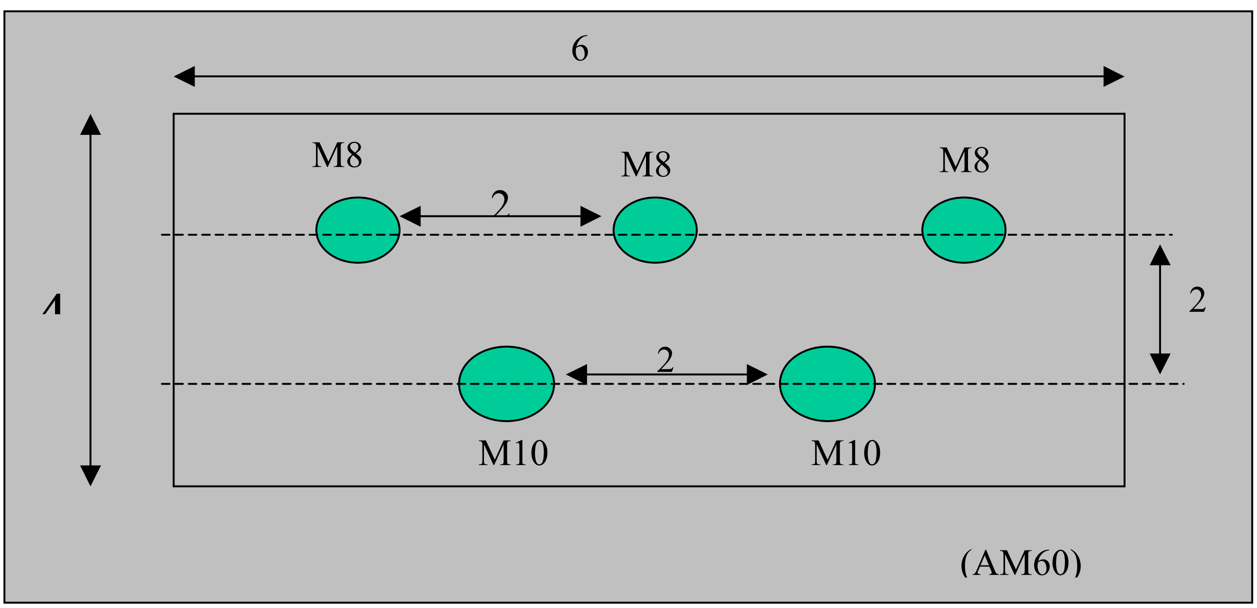
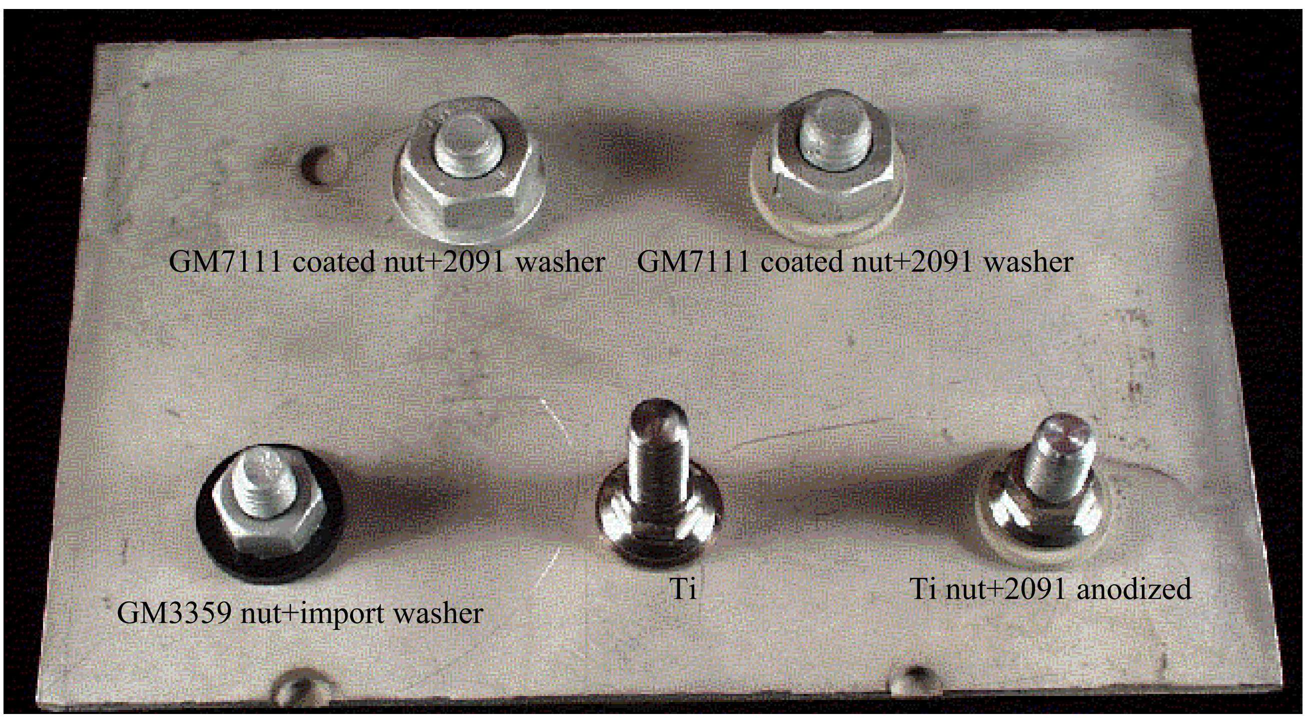


Figure 3 Layout of the M8 and M10 bolts in a 4 in. by 6 in. test plate

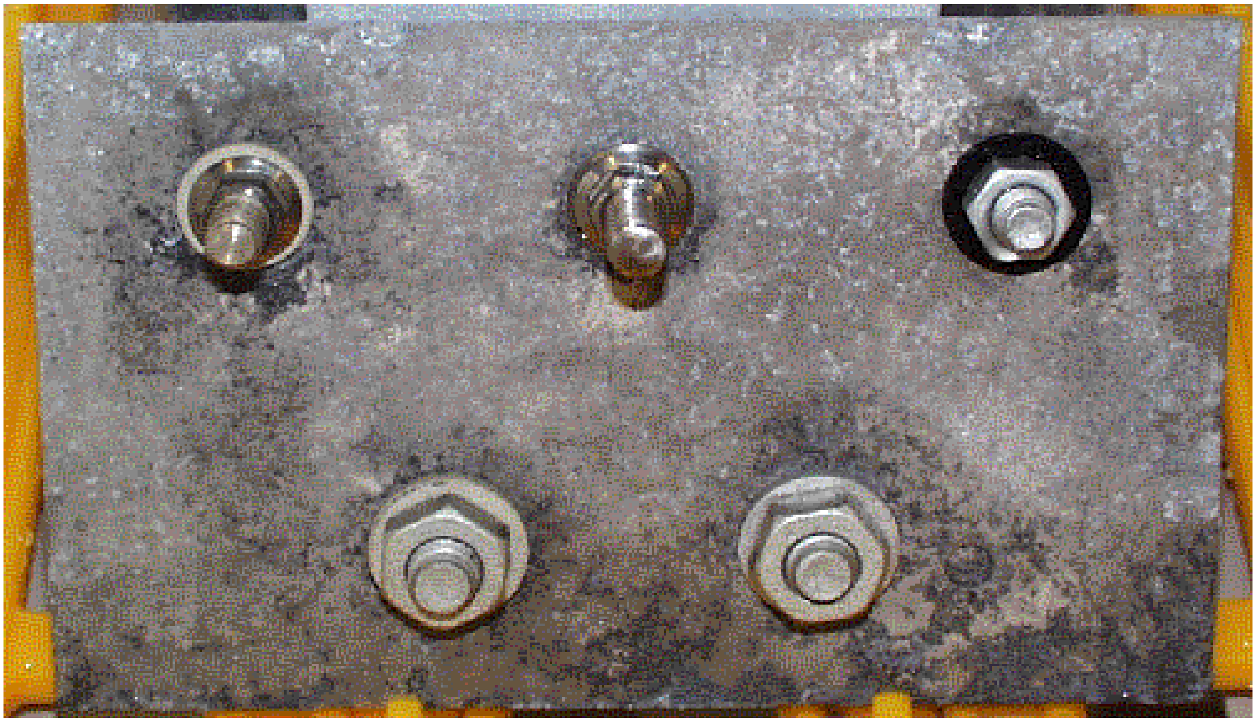
4(a)



4(b)

Figure 4 appearance of the bare Mg plate fastened with various bolts, nuts and washers. (a) the front side and (b) the back side.

5(a)



5(b)

Figure 5 Appearance of the fastened bare Mg plate after 5 cycles of GM9540P testing showing some galvanic corrosion around the bolt head where no washer is used in 5(a). 5(a): the front side and 5(b) the back side where a washer is user under the nut.

6(a)

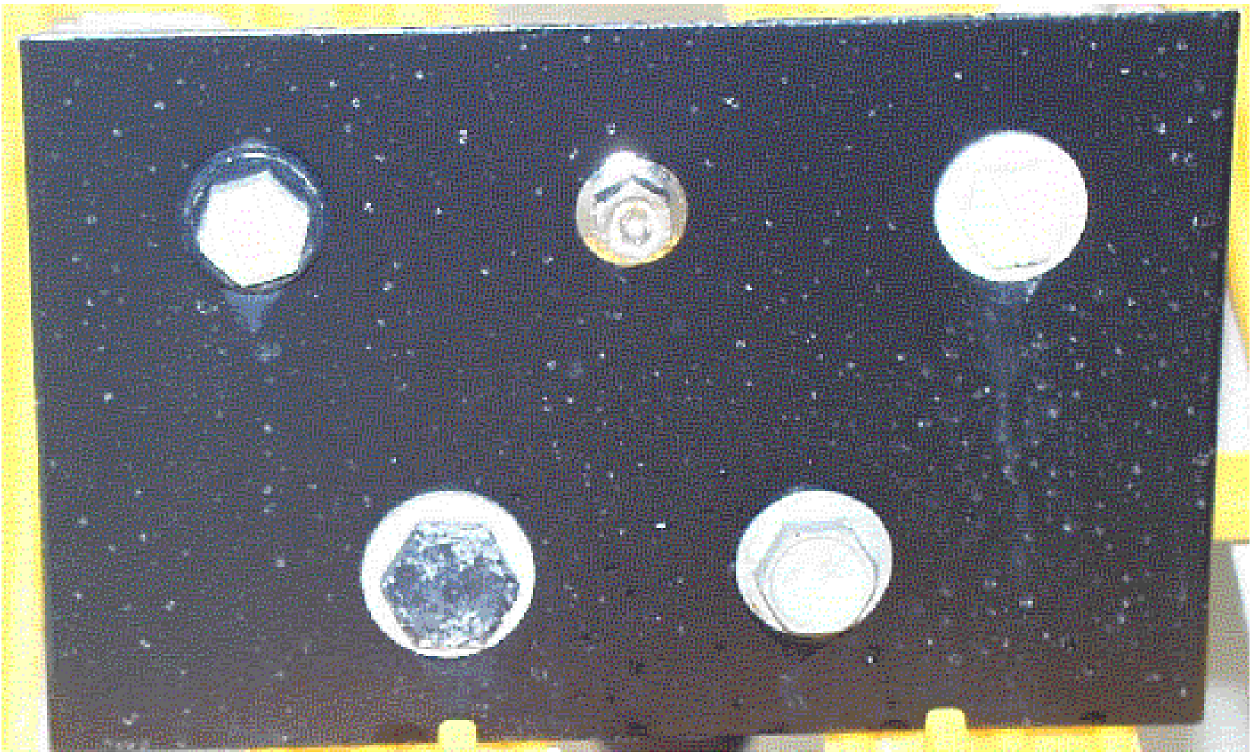
6(b)

Figure 6 Appearance of the fastened bare Mg plate after 23 cycles of GM9540P testing showing some general corrosion on both side of the plate and massive galvanic corrosion around the bolt head where no washer is used in 6(a). (a): the front side and (b) the back side where a washer is user under the nut.

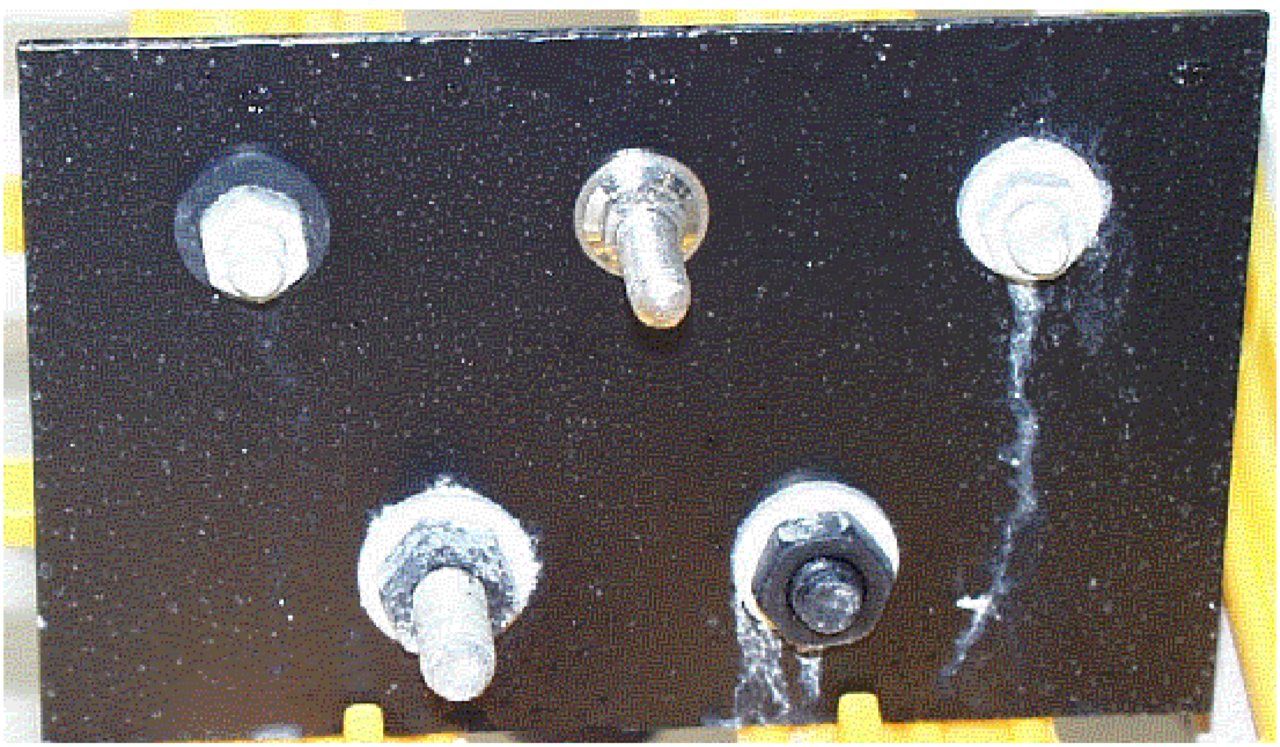
7(a)

7(b)

Figure 5 Appearance of the Mg plate coated with Alodine 5200 plus a powder coat after assembly of various fastener units. 7(a): the front side and 7(b) the back side.



8(a)



8(b)

Figure 8 Appearance of the coated Mg plate after 18 cycles of GM9540P testing.

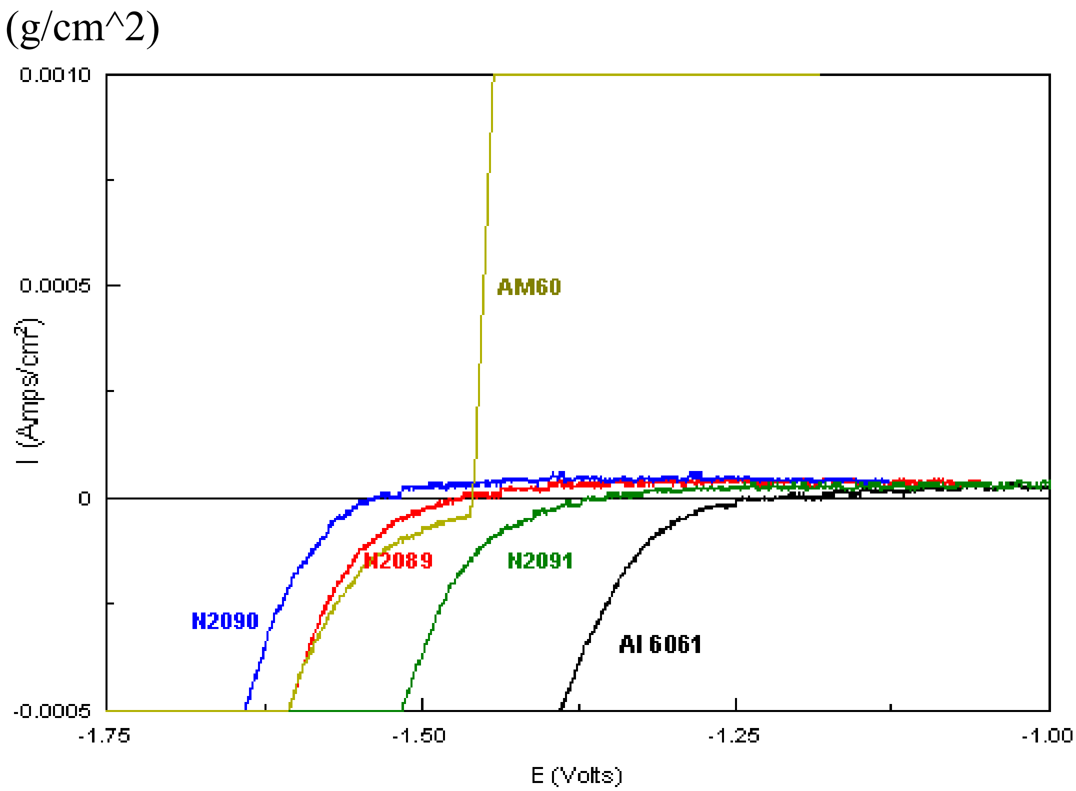


Figure 9 Polarization curves of AA 6061, AM60 and the three experimental alloys in a 1 M NaCl solution

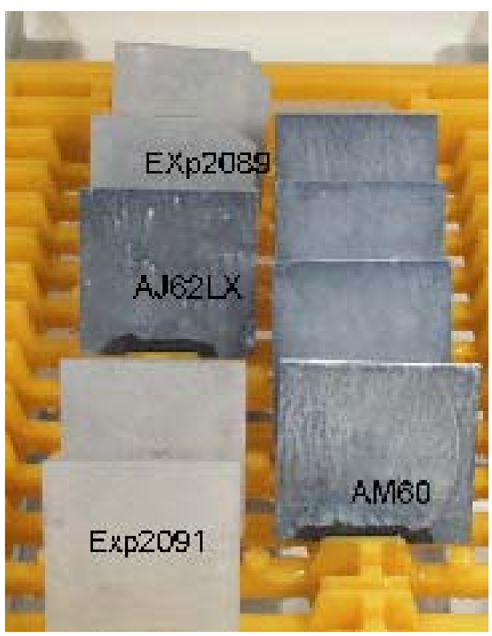


Figure 10 Appearance of test plates made of AM60, AJ62LX and two of the three new alloys (both beige color)

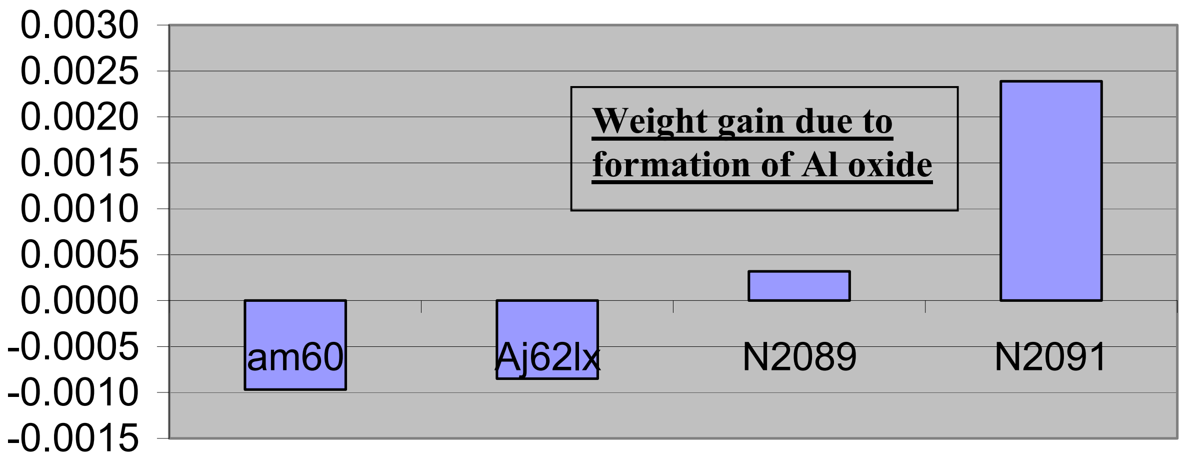


Figure 11 Weight-loss (gain) data for 4 test samples after 25 cycles of GM9540P testing

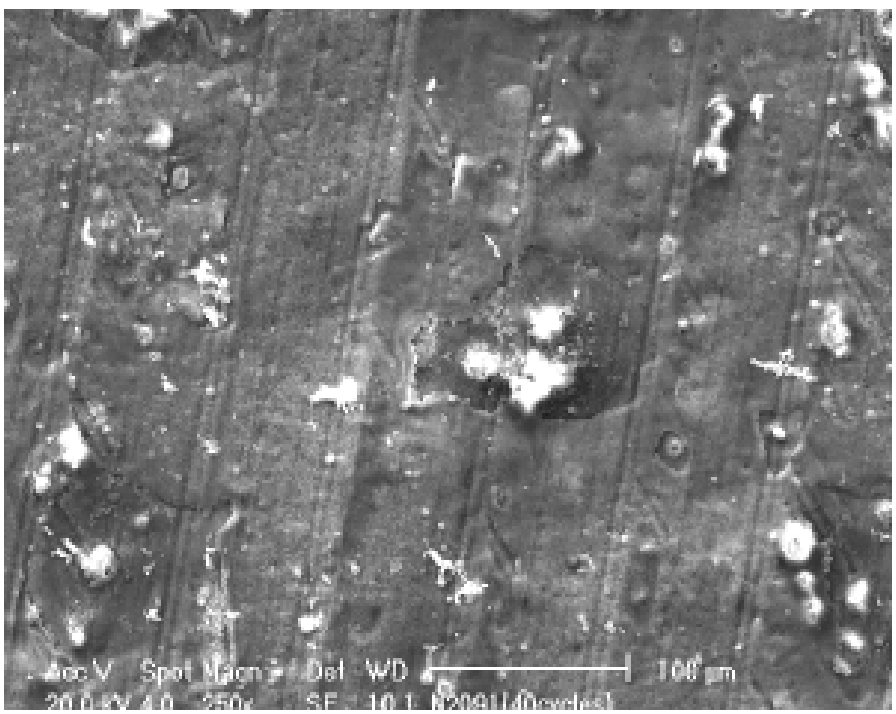


Figure 12 SEM photograph of the surface of the Exp2091 test plate after 40 cycles of GM9540P testing

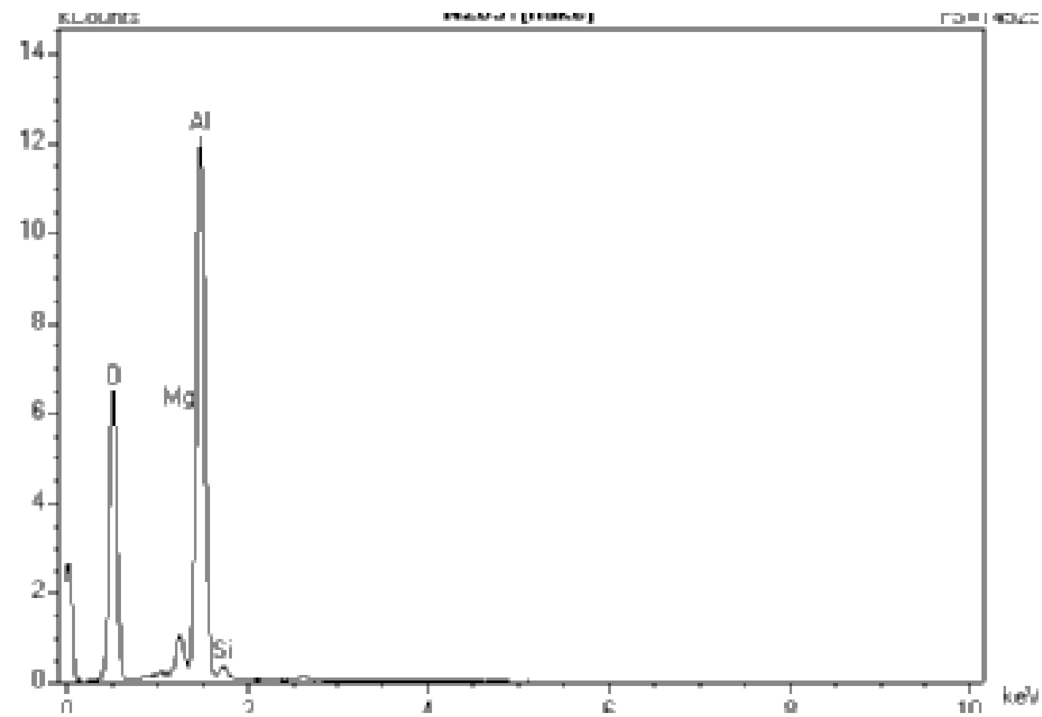


Figure 13 EDS analysis of the corrosion product on the surface of the Exp2091 plate