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RELATIONSHIP OF GRAPHITE/POLYIMIDE COMPOSITES TO GALVANIC PROCESSES

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ABSTRACT

The possibility of galvanic action between graphite composites and metals has long been recognized. Recently, at General Dynamics Fort Worth Division, it was discovered that imide-linked resins can degrade under certain laboratory conditions involving the galvanic process. The galvanic coupling was found to cause hydroxyl ions to be formed at the graphite cathode, hence attacking the O-C-N bond of the polyimide ring structure. Degradation was found to initiate at exposed graphite sites at salt water/fuel or salt water/stagnant air interfaces. The phenomena was found to occur in bismaleimides (BMI), condensation polyimides, triazines, and blends thereof. Standard galvanic protection schemes were demonstrated to be effective in preventing degradation, particularly when proper treatment of the composite was provided.

KEY WORDS: Corrosion; Graphite/Polyimides; Degradation; Galvanic Protection; Interface; BMI Corrosion

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1. INTRODUCTION

For thousands of years, humans have dealt with corrosion in marine environments. Copper nail fasteners used in ancient Roman ships corroded from contact with the hull's lead covering and salt water. The corrosion was prevented by coating the nails with lead (1). Later, in 1803, the electrochemical theory of corrosion was proposed by Wallaston (2). Shortly thereafter, in 1819, the need for dissolved oxygen in water to facilitate corrosion reactions was demonstrated by Hall (3). More recently, corrosion has been a concern for Naval aircraft, including those using graphite composites. In 1970, initial studies on metal-graphite/epoxy couples have indicated a potential galvanic metal corrosion problem with the graphite in the composite (4). Since then, protection measures have successfully been used to inhibit metal corrosion on aircraft, allowing successful service lives using graphite/epoxies.

Higher use temperature and tougher graphite composite materials have since been developed, such as bismaleimides (BMI), triazines, condensation polyimides, and thermoplastics, among others. These state-of-the-art materials allow increased aircraft performance.

In early 1990, at General Dynamics Fort Worth Division, it was discovered that imide-linked resins can degrade under certain laboratory conditions involving the galvanic process. The discovery was made while conducting solvent soak tests on composite materials. One of the solvents in the solvent-soak test matrix was an aircraft sump water condition, a combination of 3% salt water and jet reference fuel (5,6). Fluid containers used were one-gallon tin cans. Degradation in the form of resin loss resulting in loose fibers was observed after one day. The degradation initiated at composite edges and bare graphite surfaces just above the salt water interface. Tests were conducted in unusually harsh conditions: bare graphite and bare metal at 80°C. In aircraft, however, strict measures and inspection procedures are carried out to protect from corrosion.

The phenomena was found to occur in most high temperature composites with an imide linkage, including bismaleimides, triazines, and condensation polyimides.

The graphite/polyimide corrosion phenomena is a combination of previously known facts, such as galvanic coupling (7) and hydrolysis of Kapton polyimides (8,9). Like epoxies (7), graphite/ polyimide materials exhibit galvanic coupling with metals. In the past, galvanic currents and voltage measurements have been used to rank the action of various metal alloys coupled with a graphite/epoxy (7). In this study, galvanic measurements were obtained to compare the activity of different aircraft metals coupled with graphite/BMIs. Graphite/epoxy was used for comparison. Voltages and current measurements are good indicators of the severity of a corrosion problem (10,11). In addition, hydroxyl attack of polyimides is widely known in which studies have been done with Kapton films (8,9). In this study, degradation products were analyzed with infrared spectroscopy.

Protection schemes currently in use, which are used to prevent aluminum corrosion from contact with graphite/epoxy, were also demonstrated to be effective in preventing polyimide degradation.

2. DEGRADATION OF BARE COMPOSITE COUPONS

Figure 1 illustrates the setup in which BASF's IM7/5250-4 graphite/BMI coupons were placed in physical contact with the tin can in a jet fuel/salt water solution. UV Fluorescence showed the tin can to be tin (Sn) coated iron (Fe). Composite coupons used were 2.54 cm by 22.9 cm. The tape layup used was $(\pm 45)_{2S}$. This experiment was originally part of a test matrix to evaluate candidate aircraft material's resistance to various aircraft fluids. One of the fluids was fuel-tank sump water, a 50-50 (by volume) mixture of Jet Reference Fluid (JRF, TTS-735 Type VII), which



Figure 1 Setup Showing the GR/BMI-Tin Can Experiment

is a hydrocarbon fluid, and 3% by weight salt water (NaCl) (5,6). JRF/3% salt water immersions were in accordance with military specification MIL-C-27725, which is commonly used to evaluate coating and sealant performance (5,6).

In this work, the above setup will be referred to as JRF/3% salt water/Fe-Sn can. Here, the organic and aqueous phases were immiscible and formed an interface (Figure 1) referred to here as the organic/aqueous interface.

A second set of exposures included salt water exposures without fuel in a Fe-Sn can. These exposures were conducted in tightly sealed Fe/Sn cans. In this work, this experimental setup will be designated as 3% salt water/stagnant air/Fe-Sn can, and the interface will be designated as the salt water/stagnant air interface. The salt water/stagnant air condition does not apply to actual aircraft conditions, where air is convected by winds and flight.

The interface was located at approximately the mid-distance of the length of the specimen. Experiments were run at 25° C and at 80° C in a stagnant environment where the fluid(s) was left undisturbed.

Note that the above tests were harsh laboratory environments and are not realistic of aircraft environments. The Fe-Sn can provided $\sim 400 \text{ cm}^2$ of active anodic area vs. $\sim 60 \text{ cm}^2$ of bare composite area, a fraction of which were bare graphite fibers exposed through the resin. In aircraft, strict measures and inspection procedures are carried out to protect from corrosion.

Composite degradation was found to occur in bare IM7/5250-4 composite after one day exposure in the tightly sealed JRF/3% salt water/Fe-Sn can (Figure 1) and 3% salt water/stagnant air/Fe–Sn can environments. Degradation was in the form of resin breakdown of the outer plies just above the organic/aqueous interface. Location of the degradation zone was above the salt water phase. Degradation occurred wherever bare graphite was exposed just above the organic/aqueous interface. For the above tests, degradation occurred within one day at 25° C and 80° C. However, the degradation rate appeared to be much slower at the ambient temperature (25° C).

Degradation areas were different when comparing the fuel/salt water environments with the salt water/stagnant air environments. In both environments, degradation appeared to initiate via a thin film of water at the coupon surface. Thin films are known to play a significant role (12) in metal corrosion. In fuel/salt water environments, composite degradation initiation was found to occur as a result of a thin film of water traveling up the coupon surface above the interface into the organic phase. Hence, the water here was confined and subject to hydroxyl ion accumulation (see

CHEMICAL MECHANISM section). As a result, polyimide degradation initiated at the coupon surface and through time worked its way inward. In comparison, salt water/stagnant air environments exhibited degradation in the thin film of water, which condensed on the entire composite specimen above the salt water/stagnant air interface. Hydroxyl ions accumulated in the thin film, which was exposed to charged graphite fibers and BMI. The high concentration of hydroxyl ions in turn attacked the BMI. Note again that the condensation is highly unrealistic since air is convected by winds and flight in an aircraft situation, thereby preventing formation of the persisting thin water film.

As the BMI degraded, the Fe-Sn can corroded. Fe and Sn are active metals relative to graphite on the electromotive series. After exposure of about two weeks, rust plated on the graphite of the composite in the aqueous phase. As the amount of rusting increased, composite corrosion increased.

Polyimide degradation occurred only when all the following conditions exist.

- · Pooled electrolyte in contact with active metal and graphite
- Active metal and graphite of composite in physical contact
- Bare graphite of the composite at aqueous interface

Again, interface refers to organic/aqueous and aqueous/air interfaces.

In the following conditions, degradation did not occur.

- Glass/BMI scrim on surface (no graphite exposed at interface)
- 3% salt water/glass jar/no metal environments (no galvanic couple)
- Immersed in Fe-Sn can, but no physical (electrical) contact (no contact)
- Glass instead of graphite fibers (metal does not couple with glass)

Potassium dichromate inhibitor (13) was found to slow the degradation in the Fe-Sn can to five days until initiation in comparison to one day. Dichromate cartridges have a successful record in preventing corrosion from metal-metal couples in the B-58 bomber.

3. GALVANIC PROCESS MECHANISM

Figure 2 illustrates a schematic of the polyimide degradation galvanic process mechanism. Anode and cathode half reactions are listed at the top of the figure. The metal of the anode is designated 'M' to symbolize any active metal in relation to graphite. At the metal anode, metal ions go into solution sending electrons to the graphite cathode.

$$M \longrightarrow M^{n+} + ne^{-1}$$

Electrons from the ionized metal travel to the graphite allowing OH^- ions to be generated at the graphite surfaces, in contact with the aqueous phase.

$$O_2$$
 (dissolved) + 2H₂O + 4Na⁺ + 4e⁻ \rightarrow 4Na⁺ + 4OH⁻

The pH of the aqueous film above the interface was much higher than that of the bulk salt water solution. Hydroxyl ions were found to concentrate in this confined area. This is a form of "crevice corrosion" (14). pH in this area was measured to be ~13, hence polyimide attack occurred forming the amide salt (see DEGRADATION MECHANISM section for details).

 $Na^{+} + OH^{-} + POLYIMIDE \longrightarrow AMIDE SALT$

Below the interface in the bulk salt water solution, OH⁻ ions go into solution and combine with the anodic metal ions faster than they attack the polyimide. Here, pH measurements were in the





neutral range at 6.5 to 8. Because of the neutral pH, the polyimide was not degraded below the interface in these tests. The metal oxide or hydroxide is formed

 $nNa^{+} + nOH^{-} + M^{n+} \longrightarrow M(OH)_n (solid) + nNa^{+}$

where M is the anodic metal and n is the metal electron valence. Sodium was not used up in this reaction and continued in ion transport between the electrodes. In the case of an aluminum anode, $M^{n_+} = Al^{3_+}$ and the white gelatinous precipitate $Al(OH)_3$ was formed. $Al(OH)_3$ was evident at aluminum pits and the salt water interface.

In an epoxy, galvanic action caused hydroxyl ions to be accumulated above the 3% salt water interface as in the polyimide. But since epoxies are resistant to hydroxyl attack, degradation did not occur.

 $Na^+ + OH^- + EPOXY \longrightarrow NO DEGRADATION$

4. MECHANISM OF WATER CONFINEMENT IN JET FUEL PHASE

An experiment was conducted to show that water can travel up the composite surface into the organic phase, allowing polyimide degradation. Surface tension may be a driving parameter for the water travel. Figure 3 illustrates the setup, in which a very small amount, 1 to 2 ml of high pH KOH solution, was mixed with JRF in a glass beaker. The pH of the aqueous phase was measured to be 13 to 14. The aqueous phase separated from the organic phase and settled at the bottom of the beaker. The bare IM7/5250-4 was placed into the solution with the end in contact with the aqueous phase. No active metal was added, hence no galvanic cell existed.



Figure 3 Schematic of Experiment Which Proved Water Travels Up the Composite Surface Into the Jet Fuel Phase Allowing Ployimide Degradation

After one day, the high pH solution travelled up the composite surface into the organic phase. This was evident by severe degradation in the outer 1-2 plies of the coupon in the JRF phase. The degradation extended from the pool of high pH water at the bottom of the coupon. The darkened portion of the coupon shown in Figure 3 shows the degradation location. The film's travel distance above the aqueous phase is finite and limited to 3 to 5 cm above the aqueous/fuel interface.

5. MATERIALS THAT WERE AFFECTED

The Fe-Sn can experiment was used as an accelerated screening test to check various composites for the degradation phenomena. Material examinations were conducted using a JP4/3% salt water environment at 80° C. A $(\pm 45)_{2S}$ tape layup was used if available. All composite specimens were bare.

All high temperature materials with an imide linkage showed resin loss resulting in loose graphite fibers within one to two weeks. Materials affected included the following.

> Bismaleimides (BMI) Condensation Polyimides Triazines Thermoplastic Polycyanates The high temperature PMR materials

Included are high-crosslink density triazine and IM6/K-III (Avimid-K). Specimens degraded independent of ply orientation or thickness or if graphite fabric was used instead of tape. In all cases, degradation appeared in the region illustrated in Figure 1.

6. MATERIALS THAT WERE NOT AFFECTED

Materials not degraded in the JP4/3% salt water/Fe-Sn can environment included these.

Epoxies

Thermoplastics: GR/HTA and GR/RADEL-X

Poly-benzimidizole (PBI)

These materials did not exhibit noticeable cathodic hydrolysis for over 2900 hours in the JP4/3% salt water/Fe-Sn can/80° C environment. After approximately 2900 hours, a small amount of resin loss was evident at the coupon edges and surfaces above the interface location. Degradation of the type referred to in this work is not viewed as a problem for the above materials.

7. BMI HYDROLYSIS CHEMICAL REACTION MECHANISM

Degradation of Kapton film from hydroxyl attack is a widely known phenomena (8,9). Kapton film, a polyimide used for wire insulation, exhibits degradation in aqueous environments. Figure 4 illustrates the basic mechanism. As hydroxyl ions are generated at bare graphite cathodic sites, nucleophillic attack by the OH⁻ ions occurs on the carbons of BMI O-C-N bonds (arrow). This reaction opens up the polyimide ring, hence weakening the backbone structure of the material. From this reaction, the di-salt is formed, which is in equilibrium with the di-acid in the aqueous media.

Polyimides used in graphite composites have the same imide ring illustrated in Figure 4. Degradation products were a brown gummy substance. FTIR results have shown N-H groups present in the degradation products. However, broad bands covering nearly the entire spectrum



Figure 4 Mechanism of Hydroxyl Attack on Simple Polyimide Ring Structure

left no certain indication of amides. The broad bands may have resulted from impurities or from a wide distribution of molecular weight in the severed chains.

The reaction rate per unit area of polyimide is dependent on the pH or concentration of hydroxyl ions in contact with it. Rate is defined as the weight loss of polyimide per unit time or the rate of OH^{-1} ion consumption per unit time. This rate of loss is proportional to the molar density of susceptible O-C-N bonds in the polyimide. The chemical rate equation is, thus, (15)

rate/Area =
$$k(T) \times [OH^{-}]^{x}$$

where

- Area is the surface area of polyimide exposed to the high pH (cm²).
- [OH⁻] is the concentration of hydroxyl ions in the aqueous phase above the aqueous interface (mol/liter).
- k(T) is the reaction rate constant which is a function of temperature, T.
- x is the order of reaction and has been determined for Kapton films to be between 1.73 and 2.01 at pH > 14 when rate = OH^- ion consumption per unit time (8,9).

The equation shows that degradation rate increases with hydroxyl ion concentration (pH). However, degradation occurs at negligible rates with a sufficiently neutral pH. Note that concentration of hydroxyl ions is related to pH by the following equation (15).

$$pH = 14 + \log[OH^{-}]$$

The higher the galvanic current, the higher the hydroxyl ion generation.

Galvanic current is dependent on a number of variables (16,17), such as electrode surface area, distance between electrodes, nature of and percent of electrolyte in solution, temperature, and electrode polarization, among others. These conditions change with exposure time. In the case of BMI degradation, however, current increased with time after degradation was initiated. Experiments using an aluminum-IM7/5250-4 couple have shown that current increased threefold as the BMI degraded. The process accelerated itself as more bare fibers were exposed from the degradation.

8. EFFECT OF METALS ON BMI DEGRADATION

Galvanic current and voltage measurements were carried out to rank the action of various metal alloys when coupled with IM7/5250-4. A 3% by weight NaCl aqueous solution was used as the electrolyte. Composite surface area immersed in the aqueous phase was held constant at 46.6 cm^2 in all tests. Area includes 6.9 cm² of composite edge and 39.7 cm² of composite face. Metals tested were various aluminum alloys, steels, and Ti-6Al-4V.

Current measurements, which give an idea of corrosion rate or the absence of corrosion, are listed in Table 1. For current measurements, the galvanic polarization method (20) was utilized since a zero-resistance ammeter (7) was not available. Table 1 shows that the aluminum alloys gave the highest currents along with the D6AC steel. Stainless steels were less active, while titanium was relatively inactive. Values agree with those of graphite/epoxies (7). When coupled with 2024 aluminum, IM7/5250-4 gave a slightly higher current than did the IM7/8551-7A. When coupled with 2024 aluminum, scrimmed IM7/5250-4 gave a much lower current reading than did the bare IM7/5250-4, showing the scrim hinders the galvanic process. Currents below 100 microAmp were at the lower extreme of the meter scale and may not be accurate; they may be much lower. All current values can be divided by 46.6 cm² to obtain microAmps/cm².

ANODE VS. IM7/5250-4 26 PLY COMPOSITE WITHOUT SCRIN			
ANODE CUI	CURRENT (MICRO AMPS)		
ANODE CUI 2024 AI	RRENT (N 685 664 661 603 549 447 107 93 *	AICRO AMPS)	
pH 15-7 Steel	89 *		
321 Cress Steel	59 *		
IM7/8551-7A vs. 2024 Al	501		

Table 1 ELECTRICAL CURRENT MEASUREMENTS

* Current measured at lower extreme of scale - - not reliable accuracy for these pairings

Voltage differences were measured (18) with the couples listed in Table 1. Voltage differences were measured vs. a standard calomel electrode. All values agreed with those generated for graphite/epoxies (7). Values also agreed with galvanic series of various metals coupled with graphite in flowing seawater (19). When coupled with 2024 aluminum, IM7/5250-4 exhibited the same voltage as IM7/8551-7A, both in the range of 0.71-0.72 Volts.

Some of the aircraft metals mentioned above were coupled with IM7/5250-4 composite in JRF/ 3% salt water environments to examine if the galvanic action of the metals was enough to degrade the composite. This was a qualitative test to give a yes/no answer. Note that the composite and metal were bare and the temperature was held at 80° C, making the test highly unrealistic for aircraft environments. Tests were conducted in glass jars. Metals that influenced degradation within 400 hours included 2024 aluminum, D6AC steel, 321 cress steel, or PH 13-8 steel. As expected, Ti-6Al-4V did not influence polyimide degradation.

9. PROTECTION SCHEMES PREVENT DEGRADATION

Standard galvanic protection schemes, which are currently in use, were demonstrated to be effective in preventing degradation, particularly when proper treatment of the composite was provided. These proper treatments include glass/BMI scrim, coatings, and sealants. Protection schemes to prevent galvanic corrosion have been in use for many years (21).

9.1 SCRIM PLY PROTECTION

Experiments have shown that glass/BMI scrim provided excellent protection of IM7/5250-4 in the 3% salt water/JP4/80° C/Fe-Sn can. Also, galvanic current measurements of scrimmed composite with 2024 aluminum couples were low compared with bare composites.

Figure 5 illustrates the specimen design in which 26 ply IM7/5250-4 specimens were used. The specimen had 120 glass/BMI scrim on both faces. The free specimen edges were protected with polysulfide sealant to prevent the graphite from being exposed to the salt water. No graphite was exposed at the interface. Both specimen ends were sanded to allow electrical connection with the active metal of the Fe-Sn can. The coupons survived two months in this harsh environment, showing that scrim protects the composite from degradation.



Figure 5 Glass/BMI Scrim Protected the Composite in the Galvanic Environment. Graphite Was Exposed at Specimen Ends Allowing Contact with the Active Metal of the Fe/Sn Can.

Current measurements for scrimmed GR/BMI were measured to be very low in comparison with non-scrimmed GR/BMI when coupled with 2024 aluminum (Table 1). Galvanic current was minimized since cathodic area was minimized.

9.2 COATING AND SEALANT PROTECTION

In aircraft designs, it is common to bolt composite to metals, particularly to aluminum. Effects of salt fog/draining condition (22) and fuel/3% salt water environments were examined. Figure 6 illustrates the specimens used for both environments. Composites used were IM7/5250-4 and IM7/8551-7A. Aluminum was chromate anodized and coated with polyurethane coating (6) prior to drilling. Titanium bolts and cress steel nuts were used to bolt the composite to the aluminum. Polysulfide sealant (5,6) was applied to areas as shown in the figure and in bolt holes immediately prior to assembly. Resistance measurements show that a good electrical connection existed between the composite, aluminum, and bolts after assembly and sealant cure. Electrical connection between the skins and spars is an aircraft requirement for instrument grounding and lightning strike protection.

All graphite/polyimides in salt fog (22)/draining condition were undamaged after 3000 hours exposure when coupled to coated aluminum. This includes specimens with bare composite.



Figure 6 Composite/Aluminum Coupled Specimens. Polyimide Degradaton Was Not Observed in These Specimens for 3000 Hours in the Salt-Fog (22) Environment.

Polyurethane coating on the composite, which included bare graphite areas at composite edges and bolt holes, prevented polyimide degradation for 3000 hours in fuel/3% salt water/80° C immersion experiments.

9.3 SALT WATER POOLING AT ALUMINUM SPAR

Figure 7 illustrates an experiment in which normal protection prevented BMI degradation in pooling situations in salt fog. The situation is similar to that occurring on aircraft. Figure 7 illustrates the setup in which coated 2024 aluminum L-angle spars were bolted to an IM7/5250-4 panel. The panel was fabricated with 120 glass/BMI scrim on both surfaces. Aluminum was chromate anodized and coated with polyurethane coating (5,6) prior to drilling. As in the previous set of experiments, titanium bolts and cress steel nuts were used to bolt the aluminum in a "V" configuration to permit water pooling (Figure 7). Polysulfide sealant (5,6) was applied to areas as shown in the figure and in bolt holes immediately prior to assembly. The panel was placed in a salt-fog chamber at approximately 20 degrees from the horizontal. During the experiment, water was continuously replenished at the pooling area from the continuous salt spray.

After 1000 hours in the salt-fog, neither composite nor aluminum showed corrosion. A salt deposit but no aluminum pitting was present at the base of the "V." The glass scrim prevented salt water from contacting the graphite, therefore breaking the electrical circuit.

10. FIELD SERVICE SHOWS NO GR/POLYIMIDE DEGRADATION

Various aircraft have been examined for the presence of graphite/polyimide corrosion and, to date, none has been found. In May 1990, the General Dynamics' prototype F16-XL wing skins were examined with video borescopes and ultrasonic hand scanners. The wing skins were fabricated out of USPs (now BP) graphite/V378A, which was bolted to anodized/coated

aluminum spars. No polyimide corrosion was observed. Glass scrim covered the entire wingskin and protected it from corrosion. The graphite/polyimide lower strakes of the AV8B (Harrier) were investigated and BMI corrosion was not detected.



Figure 7 Standard Aircraft Protection Schemes Protected the Composite in Salt Fog/ Pooling Environment.

11. CONCLUSIONS

- 1. Graphite/polyimide degradation occurs when all of the following conditions exist.
 - · Pooled electrolyte comes in contact with active metal and graphite of composite.
 - Active metal and graphite are also in physical contact.
 - Bare graphite of composite are exposed at aqueous interface.
- 2. Polyimide degradation occurs as a result of hydroxyl ion accumulation in the thin film of water just above the salt water/fuel interface. This accumulation is a result of the galvanic process.
- Degradation as described in this work applies to graphite composites containing an imidelinked resin. The phenomena was found to occur in BMI, in condensation polyimides, and in triazines.
- 4. Degradation of the type referred to in this work is not viewed as a problem for graphite epoxies.
- 5. Standard galvanic protection schemes were demonstrated to be effective in preventing polyimide degradation, particularly when proper treatment of the composite was provided.

REFERENCES

- 1. Coburn, S.K., "Atmospheric Tests", Handbook of Corrosion Testing and Evaluation, p. 507 W.H. Ailor, John Wiley and Sons, Inc. 1971.
- Wallaston, W. H., "Electrochemical Theory of Acid Corrosion," Phil. Mag., Vol. 11, 206 (1801).
- 3. Hall, L.F., Quarterly J. Sci., Vol. 7, 55 (1819).
- 4. Sederman, R.R. and Weber, K.E., "Investigation of Galvanic Corrosion Associated with Filamentary Composites in Contact with Aircraft Structural Metals," Technical Breif, Lockheed California Company, Burbank, Calif. 1970.
- 5. Military Specification TTS-735, Type VII
- 6. Military specification MIL-C-27725
- Fiscer, P. and DeLuccia J.J., "Effects of Graphite/Epoxy Composite Materials on the Corrosion Behavior of Aircraft Alloys", *Environmental Effects of Advanced Composite Materials*, ASTM 602, American Society for Testing and Materials, 1976, pp. 50-66.
- 8. Kitayev G.A. and Krupina, T.L., Poly. Sci. USSR Vol. 29, p. 905 (1987).
- 9. Pawlowski, W.P. and Coolbaugh, D.D., Poly Mat. Sci. and Eng. Vol. 59, p. 68 (1988).
- 10. Uhlig, H.H., Corrosion and Corrosion Control, Wiley, New York, 1971.
- 11. Fontana, M.G. and Greene, N.D., *Corrosion Engineering*, McGraw-Hill, New York, 1967.
- 12. Krueger, J., Hayfield, P.C.S., "Ellipsometry in Corrosion Testing", *Handbook of Corrosion Testing and Evaluation*, p. 783, W.H. Ailor, John Wiley and Sons, Inc. 1971.
- 13. Gatos, H.C., "Inhibition of Metallic Corrosion in Aqueous Media", Symposium on Corrosion fundamentals. p.127, University of Tennessee Corrosion Conference at Knoxville, March 1,2,3, 1955.
- 14. Ailor, W.H., *Handbook on Corrosion Testing and Evaluation*, John Wiley and Sons, Inc. 1971.
- 15. Nebergall, W.H., Holtzclaw, H.F., Robinson, W.R., General Chemistry, D.C. Heath and Company (1980).
- Pourbaix, M., "Potential-pH Diagrams and Metallic Corrosion", *Handbook of* Corrosion Testing and Evaluation, p. 661 W.H. Ailor, John Wiley and Sons, Inc. 1971.
- 17. Schwerdtfeger, W.J., and Denison, I.A., "Geometric Factors In Electrical Measurements Relating to Corrosion and its Prevention", *Symposium on Corrosion Fundamentals*. p.185, *University of Tennessee Corrosion Conference at Knoxville, March 1,2,3, 1955*.
- 18. ASTM Standard G69-81; Annual Book of ASTM Standards, Vol. 03.02 (1989).
- 19. ASTM Standard G82-83; Annual Book of ASTM Standards, Vol. 03.02 (1989).
- 20. Iverson, W.P., "Tests in Soils", *Handbook of Corrosion Testing and Evaluation*, pp. 575-595, W.H. Ailor, John Wiley and Sons, Inc. 1971.
- 21. Richardson, J.I., "Coatings for Atmospheric Corrosion Protection", Symposium on Corrosion Fundamentals. p. 43, University of Tennessee Corrosion Conference at Knoxville, March 1,2,3, 1955.
- 22. ASTM Standard B117-85; Annual Book of ASTM Standards, Vol. 02.05 (1989).

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