On November 8-9, 2006, the Naval Air Systems Command (NAVAIR) conducted a government-industry workshop on the development of corrosion-resistant alloys. This is the first of four articles about the workshop in this special section on Corrosion.

Corrosion-Resistant Alloys for Naval Aviation

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The workshop was aligned with the Naval Aviation Enterprise Science and Technology Strategic Plan, and in support of the Command’s Fleet driven metric, Aircraft Ready For Tasking at Reduced Cost. The workshop focused on three classes of lightweight structural aerospace alloys: aluminum, ultra high strength steel, and cast magnesium. It provided a forum for experts from NAE, DoD, industry, and academia to share their views and recommendations. The principal goal was to identify potential science and technology approaches for the development of corrosion-resistant alloys. Over 75 national and international experts registered to participate, including representatives from the United States, United Kingdom, Canada, and South Korea. Participants included representatives from the DoD services; from the steel, aluminum, and magnesium alloys producers; from U.S. airframe manufacturers, and from academia, Table 1.

The GOTChA (Goals, Objectives, Technical Challenges, and Approaches) methodology served to structure the workshop and to help focus the efforts of the participants, as shown in the diagram. The workshop organizers identified a challenging materials property goal for each of the three alloy systems which, if achieved, could significantly impact naval aviation. For example, the goal for steel was “Ultra High Strength Intrinsically Corrosion-Resistant Steels for Enhanced Readiness, Improved Performance, and Lower Life Cycle Costs.” Similar goals were established for the aluminum and magnesium alloy systems. For each alloy system, three specific materials goals were defined. 

*Fellow of ASM International

Table 1 — Participating organizations

<table>
<thead>
<tr>
<th>Government</th>
<th>Industry</th>
<th>Academia</th>
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<tr>
<td>Air Force</td>
<td>Alcoa</td>
<td>Brown University</td>
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<td>Army</td>
<td>Allegheny Ludlum</td>
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<td>DARPA</td>
<td>Allison Transmission</td>
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<td>JSF</td>
<td>Allvac</td>
<td>Loyola Marymount</td>
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<td>Naval SWC</td>
<td>Alcan, Boeing</td>
<td>Penn State</td>
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<td>NIST</td>
<td>Carpenter Technology</td>
<td>University of Virginia</td>
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<td>Naval Research Lab</td>
<td>Goodrich</td>
<td>Pohang University</td>
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<td>OSD</td>
<td>Granta Design</td>
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<td>Office of Navy Research</td>
<td>Lambda Research</td>
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<td>OPNAV</td>
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<td>PEO(A)</td>
<td>MagElektron</td>
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<td>NAVAIR</td>
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<td>Tagnite</td>
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<td>Navy Metalworking Center</td>
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Fig. 1 — The GOTChA (Goals, Objectives, Technical Challenges, and Approaches) methodology served to structure the workshop and to help focus the efforts of the participants.
The overall cost of corrosion for the Department of Defense is between ten and twenty billion dollars per year. The cost of corrosion to the Department of the Navy has been estimated at 4.4 billion dollars. Within the Navy, the impact of corrosion on naval aviation is overwhelming. Over 100 million work hours and nearly a billion dollars were spent by NAVAIR from 1994 to 2004 on corrosion-related problems. It is important to understand that the financial impact of corrosion is just one aspect of its pernicious effects. Corrosion also affects safety and the number of aircraft ready for tasking.

Mitigation efforts

Improved maintenance and systems designs have reduced corrosion related problems. Advanced paints, sealants, and corrosion preventive compounds have also provided protection and also have mitigated the effects of corrosion. However, paints and sealants can be breached or imperfectly applied, thus exposing the underlying structure to the harsh naval environment. The traditional approach to corrosion control has been reactive and not proactive. Thus, designers have typically not considered corrosion until late in the design process. Rose et al. divided DoD response to corrosion into four categories: Repair and Maintenance; Planned Corrosion Maintenance; CPAC Methods; and Design-in Resistance. Table 2 outlines some of the merits and risks associated with two of these approaches. Designing-in corrosion resistance clearly provides the benefits of reduced lifecycle cost and enhanced readiness; however, the up-front cost may be greater.

I encourage industry-academia and government agency collaboration and dialog. Obviously, the work required to develop “intrinsically” corrosion resistant alloys is ambitious and has just begun. It will take a concerted effort of a diverse group of concerned experts to adequately address this issue.

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Acknowledgements

I would like to thank the workshop organizers, session chairpersons, and recorders, viz., Mr. Ken Clark, Prof. Omar Es-Said, Dr. Eui Lee, Dr. Will Marsden, Ms. Denise Piastrelli, Mr. Irv Shaffer, Mr. Troy Tack, Dr. Suresh Verma, Dr. Jeffrey Waldman, and Dr. Daniel Wintersheidt. I especially wish to thank the technical experts from industry, academia, and the government, who made this event a success.

The materials selected and engineered for Navy and Marine Corps aircraft are driven by the unique maritime operational requirements and harsh corrosive environment in which the aircraft operate. Carrier-based aircraft experience six times the structural loads of land-based aircraft, mainly because they must land at a sink rate of 27 feet/second, and must survive catapult launch acceleration of 150 mph in 2.1 seconds. In addition to these structural loads, the environment in which these carrier-based aircraft operate is the most severe natural corrosive environment on the planet.

The overall cost of corrosion for the Department of Defense is

Table 2 — Risks associated with corrosion mitigation strategies

<table>
<thead>
<tr>
<th>Design-in corrosion resistance</th>
<th>Repair and replace</th>
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<tbody>
<tr>
<td>Higher upfront cost, less maintenance/repair required, lower life-cycle costs, longer service life, higher reliability, higher readiness, lower risk, extended system life.</td>
<td>Lower upfront cost, more maintenance/repair, much higher life cycle cost, shorter service life, lower reliability, lower readiness, higher risk.</td>
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High-Strength Aluminum Alloys

The participants in the aluminum workshop sessions validated and amended three objectives for achieving ultra high-strength, inherently corrosion-resistant aluminum alloys for Navy aircraft.

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Science and technology objectives of the aluminum workshop were based on the goals for aluminum alloys. The goals were to develop alloys with the strength of 7075-T6, good toughness, and “immunity” to stress corrosion cracking (threshold stress >75% of yield strength).

Technical challenges were identified as:
- Lack of quantitative modeling that accepts material’s inputs.
- Lack of non-heat-treatable aluminum alloys with specific mechanical strength similar to that of 7075-T6.
- Lack of a corrosion intensity factor, and lack of ability to select accelerated corrosion or electrochemical testing to reproduce real-world results.

New aluminum alloys should not require an anodized coating, which produces a fatigue debit. Technical challenges were identified as:
- How to optimize the surface layer — de-alloying, cladding, gradient.
- Developing self-healing surface oxides via micro-alloying or other strategies.
- Incomplete understanding of how microstructural features affect corrosion behavior.

Another requirement was for an alloy that has three times the corrosion fatigue resistance of 7050-T7XX. Technical challenges are:
- Lack of understanding of microstructural features that give rise to crack initiation sites.
- Lack of understanding of damage induced by corrosion, and its transition to crack growth.
- Short-term challenge: Fine tuning 2x9x aluminum alloys.
- Lack of understanding of oxide formation and integrity on crack-growth behavior in corrosive environments.

Technical solutions
Participants then developed and prioritized approaches to overcome the technical challenges. Based on the various approaches that were discussed, critical research areas were established. If carried out, these would result in achieving the technical objectives for the aluminum alloys. Specific goals were:
- SCC improvements: The threshold strength of 7075-T6 is 75% of the yield strength. No sacrifice in specific strength and toughness values.
- 7075-T6 mechanical properties, corrosion resistance equivalent to anodizing, and no fatigue debit.
- A factor of three improvement in corrosion fatigue as compared to 7050-T7xx.

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Critical research areas for aluminum

◆ Al-Mg and Al-Mg-Li alloy research
These alloys have excellent corrosion resistance, but do not meet aerospace specific-strength requirements. Strength must be improved while retaining corrosion resistance. Improved understanding of the effects of tertiary and quaternary alloy additions on precipitate structure, morphology, matrix-precipitate interface, and dislocation-precipitate interaction.

◆ Quantitative corrosion models
Establishment of quantitative corrosion modeling that accepts material’s input and enables us to predict real time corrosion with accelerated test results.

◆ Optimized surface layer
Modification of surface layer composition can significantly improve corrosion resistance without sacrificing mechanical properties. Understanding the corrosion mechanisms associated with varying composition is necessary to optimize the surface. Techniques include laser, thermal spray, vapor deposition, nitriding, carburization, and surface diffusion.

◆ Development of self-healing surface
Some oxide layers can be healable in the presence of selected microalloying or other strategies. Must explore the mechanisms of self-healing and understand the characteristics of oxide layers based on the presence of other elements.

◆ Corrosion damage, crack initiation, and crack propagation
Mechanisms associated with corrosion crack initiation and propagation are not well understood. Mechanistic and statistal analyses are required of the crack initiation sites associated with corrosion damage in terms of size and morphology. Mechanisms associated with the formation of crack initiation must be established.

◆ Aluminum-lithium alloy design
The lack of a mechanistic understanding of the fatigue performance in corrosive environment for current Al-Cu-Li alloys 2098, 2050, 2198, 2099, 2199, and 2195 is impeding their optimization. Third-generation alloys exhibit very good resistance to fatigue and stress-corrosion cracking, but are far from achieving their full potential.
Corrosion-Resistant Cast Magnesium Alloys

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Cast magnesium alloys are widely applied in rotorcraft as gearbox and transmission housing materials. Their low density and high structural stiffness provide a means of saving hundreds of pounds per rotary aircraft compared with aluminum. Although magnesium alloys reduce structural weight, their position in the electrochemical series renders magnesium parts susceptible to severe galvanic corrosion. This is particularly true in the Navy’s harsh operational environment.

The critical technical challenges associated with achieving the objectives were discussed, and technical approaches were identified and prioritized. The following critical research areas were developed.

• Qualify and implement EV31A, Tagnite, and Rockhard.
• Research and implementation of cathodic protection schemes.
• Magnesium alloys with a self-healing passive surface.
• Advanced computer modeling to invent corrosion resistant, high-performance magnesium alloys.

Specific objectives were:
• A cast magnesium transmission gearbox with a 50% lower lifecycle cost than baseline ZE41A or AZ91C alloys.
• A magnesium casting alloy/attach point system that provides galvanic performance superior to aluminum/steel.
• A magnesium alloy designed from first principles that mimics the oxide structure of aluminum oxide (stainless magnesium).

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The participants in the magnesium working group validated and modified the science and technology objectives for achieving highly corrosion-resistant magnesium alloys for enhanced readiness, improved performance, and lower lifecycle costs.

Critical research areas for cast magnesium alloys

◆ Qualify and implement EV31A, Tagnite, and Rockhard.
   The lifecycle cost saving of 50% or more compared to AZ91E alloy/Dow 17 surface treatment system, could be achieved through the implementation of state-of-the-art alloys and materials protection schemes. Experimental work is required to resolve technical issues and validate system performance.

◆ Research and implementation of cathodic protection schemes.
   Coating protection schemes in galvanic couplings are primarily focused on the anode or magnesium alloy, but very little consideration has been given to treating the cathodic attach points that are typically comprised of aluminum, titanium, or steel. Fundamental studies are required to elucidate the payoff of novel surface modification techniques to reduce the galvanic potential with magnesium alloys.

◆ Magnesium with a self-healing passive surface.
   Magnesium oxide tends to expand and crack, resulting in an unstable and friable oxide that offers little resistance to general and galvanic corrosion. A fundamental research effort to understand oxide stability criteria, oxidation kinetics, materials property data (crystallographic and thermodynamic), and candidate alloying additions has potential to provide a suite of corrosion-resistant magnesium alloys with performance equivalent to aluminum alloy castings.

◆ Advanced computer modeling.
   With advanced computer modeling technology, alloy-design first principles may be applied to develop a model that considers (a) the effect of various alloying additions on strength, fatigue, and creep; and (b) the resulting structure of the magnesium oxide layer. Past work in alloy design, empirical property data, and oxidation characteristics would serve to guide these fundamental efforts.

◆ Corrosion damage repair.
   Advances in critical research areas will still require a means to repair corrosion and incidental maintenance damage, particularly in the depots and on ships. A fundamental processing study is required to understand the effectiveness of novel repair methods such as aluminum cold spray and brush-on Tagnite treatments. Of primary importance is the elucidation of galvanic and general corrosion behavior subsequent to repair.
The critical technical challenges associated with achieving the high-strength steel objectives were discussed and technical approaches identified and prioritized. Ultrahigh-strength steels that are inherently corrosion-resistant do not exist today. The inability to more precisely control hydrogen uptake in production lot quantities is a significant challenge. The technical challenges for each objective were categorized into the following areas:

- Mechanisms and modeling
- Manufacturing
- Materials qualification
- Design
- Return on investment

Specific objectives were:

- The lack of a mechanistic understanding of the effect of hydrogen on transgranular cracking is a major impediment to improving the SCC of ultrahigh-strength steels. AerMet 100-type alloys would provide mechanical properties with a factor of three improvement in $K_{\text{ISCC}}$. (For example, $K_{\text{ISCC}} = 70$ ksi by RSL method in 3.5% NaCl, pH 7.3, induced potential at OCP)
- Ultrahigh-strength stainless steels are needed with corrosion resistance equal to or better than the 15-5 alloy, and with tensile strength = 290 ksi, yield strength = 250 ksi, fracture toughness ($K_{\text{IC}}$) = 110 ksi, $K_{\text{ISCC}}$ = 70 ksi.
- Bearing steels with corrosion performance similar to the 15-5 alloy and wear resistance twice that of 52100 steel and/or Pyrowear 53 are needed. The lack of understanding of the relationship between the lubrication systems and wear resistance of bearing steels with a passivated surface layer impedes the development of high wear-resistance, corrosion-resistant bearing stainless steels.

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