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Grand Challenges in Metal Corrosion and Protection Research

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The quest to develop technologies that address growing societal needs, sustainability, environmentally-safe, and cost-effectiveness is ever growing. The suitability of these technologies to explore new resources in highly hostile conditions such as deep-sea and space has given greater impetus to corrosion research. A glance at the periodical table of elements suggests that the vast majority of the elements employed to manufacture engineering structures and devices that are integral parts of our life are thermodynamically favorable for corrosion in the chemical environments they inhabit. Additionally, miniaturization of devices and light-weighting engineering structures allow less leeway for corrosion for satisfactory performance of these components. At times, the materials made for such components are at odds with their ability to resist corrosion failures. Corrosion research, therefore, needs to involve finding ways and means to protect these materials against such failures. Although they are destined (thermodynamically) to corrode in typical chemical environments they need to serve (Pourbaix, 1974). Therefore, effective control of corrosion failures cannot involve just using the "right materials", as that may not be practically possible. Taming of environments through inhibitors and application of coatings, electrochemical means such as cathodic and anodic protection, and engineering means like structural design help to mitigate corrosion effectively. Emphasis is also placed on corrosion monitoring, inspection, life prediction, and proactive management of assets. In all these cases, understanding corrosion phenomena involving metal and environment interaction is essential.

The multidisciplinary nature of corrosion possesses more significant challenges and provides vast opportunities for corrosion researchers (NAP, 2011). Some of the critical areas are highlighted here.

CORROSION MECHANISMS

Since thermodynamic immunity against corrosion for the vast majority of elements does not exist, the route to increase their service life is to increase their kinetic resistance to corrosion. Raising the kinetic resistance of metals and alloys hinges on understanding corrosion mechanisms at macroscopic, microscopic and atomic levels (Marcus, 2012). At the moment, we have challenges to resolve and quantify chemical, electrochemical, and mechanical-including environmental flow-aspects of corrosion at these levels. Addressing these issues will go a long way in designing alloys against various types of corrosion and predicting and proactively managing corrosion.

CORROSION RESISTANT ALLOY DEVELOPMENT

Energy-efficient and eco-friendly technologies in general and technologies that involve harnessing non-conventional energies such as solar and hydrogen, deep-sea exploration and use of lean grade fossil fuels, in particular, more often than not involve the engineering structures that are exposed to highly hostile environments. Therefore, these technologies require high-performance alloys and materials. Alloy development includes, but is not limited to, the study of corrosion behavior of nanomaterials, amorphous, high entropy alloys, biomaterials, etc.

ALLOY PROCESSING AND FABRICATION CORROSION

Generally, the metallurgical structure of typical alloys is influenced by the way they are processed and fabricated, which in turn affects the corrosion properties of the alloys. With the advent of additive-manufacturing, also popularly known as 3D printing, this aspect becomes even more important (Bourell et al., 2020). Further, the metallurgy of the fabricated metals, such as those subjected to metal joining and metalworking, is influenced by the fabrication condition like temperature and pressure. As a result, the fabrication techniques influence corrosion of metals. Such studies relating alloy processing, fabrication, metallurgy and corrosion are therefore important.

SURFACE TREATMENT AND COATING

Not all engineering alloys, otherwise having desirable properties, are resistant to corrosion. Nor may it be possible to improve their inherent corrosion resistance to the desired level. Surface treatments and coatings provide the means to employ such metals for the desired applications. At the same time, growing environmental concern has made several surface treatment processes and coatings obsolete. Therefore, developing the science and technology of environmentally friendly multifunctional and smart coatings is essential. For example, coatings need to offer not only the corrosion resistance, but also other properties such as wear resistance, biocompatibility, and in the case of photovoltaic cells transparency to light and thermal insulation. In places where corrosion due to local damage of the coatings must be prevented, these coatings need to be smart to detect and heal the damaged location. Developing metallic and non-metallic coatings having one or more of the above properties can make big strides in mitigating corrosion of devices and engineering structures.

COMPUTATIONAL MATERIALS SCIENCE, DATA ANALYTICS, MACHINE LEARNING, AND ARTIFICIAL INTELLIGENCE

These tools are expected to overcome the limitations of experimentation and deterministic approaches to understanding corrosion phenomena. These tools are poised to make great impacts in advancing corrosion science and technology, especially in designing new corrosion-resistant alloys for addressing materials application to highly corrosive conditions and predicting the life of structures against corrosion. However, concerted research is needed to successfully employ these tools for corrosion science and engineering (Coelho et al., 2022).

ADVANCED/NOVEL EXPERIMENTAL TECHNIQUES FOR CORROSION RESEARCH

Understanding corrosion mechanisms involves probing the metallic systems at different scales. Therefore, research to develop techniques that resolve corrosion processes at different scales is essential.

In summary, most materials, especially metallic alloys, employed for manufacturing engineering structures and devices have a thermodynamic tendency to corrode when they are exposed to chemical environments. Only through increasing the kinetic resistance for corrosion of these materials can one raise the service life of components. For this to occur, corrosion mechanisms need to be understood. On one hand, with growing technological advances, there is a need to develop alloys to resist highly hostile corrosive environments. On the other hand, with newer manufacturing technologies, such as additive manufacturing, we need to understand the corrosion behavior of materials manufactured through newer technologies and routes. As coatings remain one of the most widely employed corrosion prevention methods, changing environmental regulations and advanced technologies call for new generation coatings. The limitations of experimental research need to be overcome. Therein lies the need for Computational Materials Science, Data Analytics, Machine Learning, and Artificial Intelligence.

AUTHOR CONTRIBUTIONS

VR provided the conceptual input for the work and wrote the document.

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