CORROSION SCIENCE:
MODERN TRENDS AND APPLICATIONS

Editors:

N. Suresh Kumar,
P. Banerjee, H. Manjunatha
& K. Chandra Babu Naidu

Bentham Books

Corrosion Science: Modern Trends and Applications

Edited by

N. Suresh Kumar
Department of Physics
JNTU College of Engineering
Anantapuramu-515002
Andhra Pradesh
India

P. Banerjee
Department of Physics
GITAM Deemed To Be University
Bengaluru Campus
Bengaluru
India

H. Manjunatha
Department of Chemistry
GITAM Deemed To Be University Bengaluru Campus
Bengaluru -562163, Karnataka
India

&

K. Chandra Babu Naidu
Department of Physics
GITAM Deemed To Be University
Bengaluru Campus
Bengaluru
India

Corrosion Science: Modern Trends and Applications

Editors: N. Suresh Kumar, P. Banerjee, H. Manjunatha & K. Chandra Babu Naidu

ISBN (Online): 978-981-14-8183-3

ISBN (Print): 978-981-14-8181-9

ISBN (Paperback): 978-981-14-8182-6

Published by Bentham Science Publishers Pte. Ltd. Singapore.

BENTHAM SCIENCE PUBLISHERS LTD.

End User License Agreement (for non-institutional, personal use)

This is an agreement between you and Bentham Science Publishers Ltd. Please read this License Agreement carefully before using the ebook/echapter/ejournal (**"Work"**). Your use of the Work constitutes your agreement to the terms and conditions set forth in this License Agreement. If you do not agree to these terms and conditions then you should not use the Work.

Bentham Science Publishers agrees to grant you a non-exclusive, non-transferable limited license to use the Work subject to and in accordance with the following terms and conditions. This License Agreement is for non-library, personal use only. For a library / institutional / multi user license in respect of the Work, please contact: permission@benthamscience.net.

Usage Rules:

1. All rights reserved: The Work is the subject of copyright and Bentham Science Publishers either owns the Work (and the copyright in it) or is licensed to distribute the Work. You shall not copy, reproduce, modify, remove, delete, augment, add to, publish, transmit, sell, resell, create derivative works from, or in any way exploit the Work or make the Work available for others to do any of the same, in any form or by any means, in whole or in part, in each case without the prior written permission of Bentham Science Publishers, unless stated otherwise in this License Agreement.
2. You may download a copy of the Work on one occasion to one personal computer (including tablet, laptop, desktop, or other such devices). You may make one back-up copy of the Work to avoid losing it.
3. The unauthorised use or distribution of copyrighted or other proprietary content is illegal and could subject you to liability for substantial money damages. You will be liable for any damage resulting from your misuse of the Work or any violation of this License Agreement, including any infringement by you of copyrights or proprietary rights.

Disclaimer:

Bentham Science Publishers does not guarantee that the information in the Work is error-free, or warrant that it will meet your requirements or that access to the Work will be uninterrupted or error-free. The Work is provided "as is" without warranty of any kind, either express or implied or statutory, including, without limitation, implied warranties of merchantability and fitness for a particular purpose. The entire risk as to the results and performance of the Work is assumed by you. No responsibility is assumed by Bentham Science Publishers, its staff, editors and/or authors for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products instruction, advertisements or ideas contained in the Work.

Limitation of Liability:

In no event will Bentham Science Publishers, its staff, editors and/or authors, be liable for any damages, including, without limitation, special, incidental and/or consequential damages and/or damages for lost data and/or profits arising out of (whether directly or indirectly) the use or inability to use the Work. The entire liability of Bentham Science Publishers shall be limited to the amount actually paid by you for the Work.

General:

1. Any dispute or claim arising out of or in connection with this License Agreement or the Work (including non-contractual disputes or claims) will be governed by and construed in accordance with the laws of Singapore. Each party agrees that the courts of the state of Singapore shall have exclusive jurisdiction to settle any dispute or claim arising out of or in connection with this License Agreement or the Work (including non-contractual disputes or claims).
2. Your rights under this License Agreement will automatically terminate without notice and without the

need for a court order if at any point you breach any terms of this License Agreement. In no event will any delay or failure by Bentham Science Publishers in enforcing your compliance with this License Agreement constitute a waiver of any of its rights.

3. You acknowledge that you have read this License Agreement, and agree to be bound by its terms and conditions. To the extent that any other terms and conditions presented on any website of Bentham Science Publishers conflict with, or are inconsistent with, the terms and conditions set out in this License Agreement, you acknowledge that the terms and conditions set out in this License Agreement shall prevail.

Bentham Science Publishers Pte. Ltd.
80 Robinson Road #02-00
Singapore 068898
Singapore
Email: subscriptions@benthamscience.net

CONTENTS

PREFACE

According to the European Federation of Corrosion, the term corrosion signifies an irreversible process due to an interaction with the environment, which causes detrimental effects on the materials permanently. For any industrial applications, this process has a severe impact on revenue. For our health and environment, it can damage several vital sections. There is a severe impact on the GDP of the country as well due to the overall damages. In this sense, the investment of scientific talent for the control of corrosion is always economically justified for mankind.

The overall growth of the Industry 4.0 and subsequent demand for new innovative materials opens a new field of mechanism to control premature degradation of the material. This book entitled 'Corrosion Science-Modern Trends and Applications' with twelve high-quality chapters provided the required picture of the recent contribution and development in the field of corrosion.

Chapter 1 presents the accelerating corrosion test method with various operating apparatus designed by ASTM standard guide. Another most important use of electrochemical techniques, namely linear polarization, potentiodynamic polarization and electrochemical impedance spectroscopy, discusses measuring the corrosion rate for coated and painted specimens.

Chapter 2 discusses various anticorrosive coatings, namely barrier, inhibitive, sacrificial, inorganic, and organic coatings. The various modified coatings are introduced to reduce pores and defects observed in conventional coatings.

Chapter 3 reviews corrosion of electronic printing board with the possibilities and types of the corrosion as well as their protective phenomena. The chapter highlights the corrosion in electronic gadgets and printed electronic circuit board since nowadays, which have printed electronic circuit board.

Chapter 4 contains a discussion on protective materials like conductive polymer and its composites such as conducting polymers mixers of magnetic materials and graphene additives on corrosion resistance capabilities.

Chapter 5 discusses corrosion protection in drinking water systems. The chapter presents corrosion of drinking water distribution system (DWDS) based on various parameters like pH of water, the hardness of water, alkalinity of water, buffer intensity, total dissolved oxygen and total inorganic carbon and organic carbon.

Chapter 6 concentrates on the corrosion of concrete. The electrons can move in the steel rebar, and the ions can move in the concrete, which acts as an electrode leading to the corrosion in concrete. To know the damage of the reinforcement in the concrete X-ray microcomputed tomography is employed.

Chapter 7 presents the corrosion effect on the aluminium alloy. The damage caused by the Sulfate Reducing Bacteria (SRB) is discussed here. The microstructure cracking occurs due to many factors like corrosion, mechanical stress, thermal stress and bacterial adherence.

Chapter 8 focuses on the corrosion problems of nuclear waste systems because of the disposal. The discussion between the rate of corrosion of all the nuclear waste packages with the nuclear waste disposal concept and the safety measures of the landfill sites is featured. Furthermore, the corrosion of the various kinds of nuclear waste packages, and the metallic container for the high-level waste packages review given the deterioration or dissipation processes, the experimental in-situ approaches, and the exemplary of corrosion of nuclear waste and lifetime forecasting are presented in this chapter.

Chapter 9 presents the impact of Microbiologically influenced corrosion (MIC) in various fields like industries related to healthcare, marine, petroleum, and oil. An attempt is made to present MIC and its underlying mechanisms. Cathodic depolarization theory, along with the other mechanisms supporting MIC caused by sulfate/nitrate-reducing bacteria, has been the focus of this chapter.

Chapter 10 recognizes corrosion as a severe problem in the power plant sector. Corrosion gives rise to wastage of material in huge quantities, failure of tubes, leakage of tubes, sudden shutdowns as well as the reduction in the lifetime of components. Also, it reduces the thermal and electrical efficiency of a power plant to a maximum extent leading to minimum maintenance, outage, and replacement cost.

Chapter 11 depicts the impacts of corrosion on significant industries in chemical and fertilizers industries. In this chapter, they focus on corrosion related to chemical and fertilizer industries, the impact of corrosion on their efficiency, corrosion controlling methods and their interrelated phenomena.

Chapter 12 focuses on Marine corrosion, its mechanism, factors affecting corrosion, and several methods adopted for the prevention of corrosion describes with an emphasis on marine corrosion inhibitors. The use of inorganic compounds and paints as corrosion inhibitors is discussed in the chapter.

K. Chandra Babu Naidu
Department of Physics
GITAM Deemed To Be University, Bengaluru Campus
Bengaluru-562163, Karnataka
India

List of Contributors

A. Manohar	Department of Materials Science and Engineering, Korea University, 145 Anam-ro Seongbukgu, Seoul 02841, Republic of Korea,
A. Franco	Instituto de Física, Universidade Federal de Goiás, Goiânia, Brazil
B. Parvatheeswara Rao	Department Of Physics, Andhra University, Visakhapatnam-530003, India
B. Venkata Shiva Reddy	Department of Physics, The National College, Bagepalli-561207, Karnataka, India
D. Chandra Sekhar	Department of Physics, Govt. College (A), Anantapuramu-515002, A.P, India
D. Baba Basha	Department of Physics, College of Computer and Information Sciences, Majmaah University, Al'Majmaah, Saudi Arabia
H. Manjunatha	Department of Chemistry, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
K. Ram Mohan Rao	Department of Chemistry, GITAM Deemed to be University, Visakhapatnam 530045, Andhra Pradesh, India
K. Haripriya	Department of Anaesthesia, MIMS Medical College, NTR University, Vijaywada, Andhra Pradesh, India
K. Chandra Babu Naidu	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
K. Venkata Ratnam	Department of Chemistry, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
K. Chandra Babu Naidu	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
M.S.S.R.K.N. Sarma	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
M. Ajay Kumar	Seongbuk-gu, Seoul 02841, Republic of Korea, Seongbuk-gu, Seoul 02841, Republic of Korea
M. Balaraju	Department of Chemistry, PSC & KVSC Govt. Degree College, Kurnool-518502, A.P, India
N. Suresh Kumar	Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P, India
N.V. Krishna Prasad	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
N. Suresh Kumar	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India
U. Naresh	Department of Physics, BIT Institute of Technology, Hindupur, A.P, India
T. Anil Babu	Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India
P. Banerjee	Department of Physics, GITAM Deemed to be University, Bangalore campus, Visakhapatnam 530045, Andhra Pradesh, India

S. Ramesh	Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India

CHAPTER 1

Testing the Types of Corrosion

D. Chandra Sekhar[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3,4] and **T. Anil Babu**[3]

[1] *Department of Physics, Govt. College (A), Anantapuramu-515002, A.P., India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[4] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

Abstract: This chapter presents the accelerating corrosion test method with various operating apparatus designed by ASTM standard guide. It is used to measure the corrosion resistance of coated and painted samples. The important uses of electrochemical techniques are linear polarization, potentiodynamic polarization, and electrochemical impedance spectroscopy. These are discussed in measuring the corrosion rate for coated and painted specimens.

Keywords: Corrosion, Electrochemical Cell, Electrochemical Impedance Spectroscopy, Salt Fog Test.

1. INTRODUCTION

In the early 1900s, the accelerated corrosion test method of metallic coatings was initially established for testing the samples, thereby improving the efficiency and durability. The test processes for corrodibility of nonferrous, ferrous metals, inorganic, and organic coatings were increased. The changes observed were added for useful testing of new materials. The service durability, and quality of samples were tested using accelerated corrosion tests. Further, these were used in material research. The ASTM International, the Society of Automotive Engineers (SAE), the Federation of Societies for Coatings Technologies (FSCT), and others established many accelerated corrosion tests, and provided variations in technical fields as well as industrial materials. As the water-based coating technology continues to evolve, one of the significant challenges that increases their anti-

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India; Tel: +91-81211 27157; E-mail: sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

corrosion performance. Some powder coatings, and their application methods were developed to decrease the usage of solvents, and applications. Subsequently, the material market made a drastic increase in the coatings, and the surface coatings were proven to have longer warranties for market challenges. The oldest accelerated corrosion testing method was ASTM B 117 standard operating Salt Spray (Fog) Apparatus. A recent development was used to measure the corrosion rate of metallic coatings in a “near-shore” atmosphere. A corrosion test was applied to determine the efficiency of material samples, and furthermore, these were used in the development, and modifications for applications in the environmental, and material sciences. Hence, the corrosion rate of the test specimen was measured using the several types of accelerated corrosion testing methods to be described at present.

2. SALT-SPRAY (FOG) TEST

The corrosion resistivity can be determined by using the Standard test ASTM B 117 for inorganic, and organic coatings applied to the metals [1]. The B 117 Standard was made up of static (constant) condition, and continuous test, which was ideally carried out in multiples within a 24-hour period. The cabinet consists of an atomized solution, which was prepared by using 5% sodium chloride, and 95% by mass of ASTM D 1193 Type IV water. This kind of cabinet can be called a salt Fog chamber. The test samples were exposed to this salt fog environment. The chamber contains an atomized solution which was held at a temperature of 35°C, and 95% relative humidity. To preserve these conditions, the chamber was heated, and it was also necessary to maintain wet conditions at the bottom of the exposure zone. The corrosion resistance of various Al and Al/Zn-coated AZ91D Mg alloys was estimated by the salt spray method. After exposing it within the salt spray chamber for one hour, fast corrosion can be occurred on the bare surface of Mg alloy, causing the loss of metallic lustre. After 8 hr of salt spray test, the Al coated Mg sample maintains its integrity, and the appearance of silver-grey surface indicating improved corrosion resistance [2].

3. MODIFIED SALT FOG TESTS

3.1. Acetic Acid Salt Spray (Fog) Test

ASTM G 85 was observed to be the modified salt fog test, which includes five annexes. The primary one is the acetic acid-salt fog test, in which the salt solution was prepared according to the B 117. Afterwards, the pH values were maintained within the range from 3.1 to 3.3 to the acetic acid. The acetic acid-salt spray test can be used for decorative chromium plating on steel [3]. The test duration should be 144-240 h. It can be used to test the metallic coatings, inorganic, and organic coatings for resistance to the highly corrosive environment in comparison with the ASTM B 117.

3.2. Cyclic Acidified Salt Fog Test

In the case of the second annex of the cyclic acidified salt fog testing, the ASTM G 43 was used for exfoliated tests on certain aluminium alloys [3]. It was generally indicated as the MASTMAASIS test, which can be used for exfoliation testing of aluminium. This test uses 5% of sodium chloride solution, and it makes it easy to adjust pH in the range of 2.8 to 3.0 with acetic acid. The test duration was noted to be 6 h cycle of ¾ h spray; 2 h dry air purge and ¾ h soak at high humidity. The temperature of chamber exposure was held at 49°C, and the tower of humidity was operated at 57°C. During the purge cycle, the objective of the test can be the drying process of samples, and further leaving a white corrosion product.

3.3. Acidified Synthetic Sea Water (Fog) Test

In annexe 3, this testing can increase the application for manufacturing the control of exfoliation-resistant heat treatments used in producing 2, 5, and 7 K series of aluminium alloys. Then, the pH value was observed to be 2.5 - 3.0, and the testing method was operated at 49°C. The modified method was used to test the corrosion rate of organic coatings applied on metallic substrates while the testing procedure was operated between 24 to 35°C. At the time of this test operated at 1 to 2 ml/h, the collection rate specified for fog cycles was the same as the use of B 117 Standard. However, 2 h cycles were used for the whole test period. Due to the cyclic nature of this test, it was necessary to develop and confirm proper condensate collection rates by using 16 h salt fog test to be conducted periodically [4]. The apparatus in the test chamber must be controlled, and hence that will cycle the exposure zone run throughout ½ h salt spray, 1 ½ h of soaking time at 98% of relative humidity.

3.4. Salt/SO_2 Spray (Fog) Test

Standard ASTM G85 Annex 4 is a salt/SO_2 fog (spray) test, which can be performed using either sodium chloride solution or synthetic sea salt solution. Like the salt spray test, it was performed at 35°C. The fog may be continuous or infrequent. In case of the operation of the cycle during the test period, the sulfur dioxide can be injected into a chamber. Herein, for ½ h salt fog, and ½ h SO_2 were

CHAPTER 2

Anti-Corrosion Coating Mechanisms

D. Chandra Sekhar[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3,4] and **T. Anil Babu**[3]

[1] *Department of Physics, Govt. College (A), Anantapuramu-515002, A.P., India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[4] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

Abstract: This book chapter discussed the various anticorrosive coatings, namely barrier, inhibitive, sacrificial, inorganic coatings, organic coatings, surface treatment, and importance of inhibitors to reduce the corrosion rate in metal and alloys. The various modified coatings were introduced to reduce pores, and defects observed in conventional coatings. The water permeability through the barrier coatings was also reduced using pigmentation of organic coatings.

Keywords: Anticorrosive, Hybrid inorganic-organic Coatings, Inhibitors, Inorganic and Organic Coatings, Sacrificial Coatings.

1. INTRODUCTION

In general, metals can be protected from corrosion using anticorrosive coatings categorized according to the mechanical process. The three basic anticorrosive coatings were known to be the protection of barrier, the effect of inhibitor (passivated substrate surface), and sacrificial type protection (galvanic effect). The small permeability of ions, gases, and liquids in a coating used for the substrate's surface provides a barrier layer which prevents the transportation of combative specimen into the substrate's surface. The chemical conversion layer coatings and inhibitive coatings provide the passivation of the substrate surface. The extensive application of metallic, organic, and inorganic coatings offers

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India; Tel: +91-81211 27157; E-mail: sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

sacrificial protection to protect metals against corrosion. An electrochemical metal with sacrificial corrosion can be protected if the metal is in electric contact with the substrate [1]. A few review studies on metallic coatings were reported [2, 3].

2. DIFFERENT COATING MECHANISMS

2.1. Barrier Coatings

Primer, topcoat, or intermediate types of barrier coatings were used frequently on immersed structures [4]. In general, the use of iron oxide, titanium dioxide, and lamellar aluminium in a small amount of pigmentation can illustrate the barrier coatings. The concentration of lower pigment volume introduces densified nature of cohesive coatings. At this juncture, the permeability can be lower towards combative specimens than either of the two other types of coatings [5]. The protection rate provided by a barrier coating system depends largely on the thickness of the coating system, the standard type, and nature of the binder system.

In literature, it was reported that the delamination of both less defective, and degraded barrier coatings significantly was reduced while increasing the thickness of the coating [6, 7]. Because coatings can act as impermeable films [8]. Indeed, the anticorrosive efficiency of barrier coatings was enhanced due to the use of the thickness of the same film which was built from several thin coats instead of a singular coat [9]. These coatings provided a barrier to prevent the corrosion, non-permeability of both oxygen, and water from the surroundings [10]. The protective mechanism of the barrier depends on the non-permeable ions into the coatings [11 - 13]. The humidity at the interface of substrate-coating contains a large electrical impedance due to the ionic impermeability of barrier coatings. Hence, the transfer of corrosive current from anode to cathode was decreased due to less conduction of the electrolyte solution at the substrate [3]. Cathode protective mechanism was added to the barrier coatings to prevent the damage of the substrate. The main role of the cathode protection mechanism would affect the external current to the specimen. Two distinct approaches are availed to produce external current:

- The noble specimens used as sacrificial type anodes are bonded by metals.
- Since external current source is used as a rectifier. The use of referred electrode shall control the current *via* a rectifier.

The use of sacrificial anodes can protect several offshore systems. This may even be only the protective system on submerged parts of the structures. Low-cost aluminium alloys as sacrificial anodes were used to protect the steel on the offshore structure in seawater. Zinc anodes also act as sacrificial anodes which were generally applied on offshore coated and buried structures of pipelines, whereas the low current density of aluminium sacrificial anodes offers high passivation. The magnesium sacrificial anodes acquired a large driven potential which was compared with zinc and aluminium anodes. Hence, magnesium anodes were used to a great extent for some applications in large resistivity atmosphere, like the structure of steel in soil, and in the heated water container for pure water. The main advantages of impressed current compared with sacrificial anodes were lower anode weight and lower drag forces from the sea. According to theory, the impressed current compared with sacrificial anodes shows economically beneficial while practically expresses the disruptions of the protective system of impressed cathode current, and its applications which were pervaded into current systems [14].

Another challenge is the combination of cathodic protection and coatings, which were applied to alkali specimens obtained from hydroxyl ions. These were formed with the oxygen reduction process. It indicates that the coatings in combination with cathodic protection cannot suitable choices for saponification. The good barrier coatings were produced using some binders. The use of polymers of hydrolyzed steady bonds, *e.g.,* epoxies and urethanes, produced the barrier coating systems much better than polymers containing several hydrophilic groups, *e.g.,* alkyds [15, 16]. The presence of polar groups usually increases the adhesive strength to the substrates of metals due to the polar groups. These were bind to the surface of metal-oxide through the bonds of hydrogen element [16]. Moreover, the restriction of binder choice depends on the nature of the environment where the barrier coatings were used. The well-designed barrier coatings can reduce the corrosion under the demand of specific requirements in addition to the combinations of inhibitors, immersed in fresh and burial soils, seawater, and well service in high corroded environments. The more crosslink density became a key element for the greater efficiency of barrier coatings [17, 18]. Several research studies emphasized ionic conduction process in the coatings [19 - 21], and the direct relationship between the existence of small crosslinked density in a film and the formation of under film type corrosion [22].

2.2. Sacrificial Coatings

The design of sacrificial coatings depends on the principle involved in the galvanic type of corrosion. These coatings were used to protect the metals from corrosion. The use of more electrochemical active metal/alloy in sacrificial coatings results in the strong protection of the substrate. Hence, the coatings were

CHAPTER 3

Corrosion in Electronics

U. Naresh[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3,4], **A. Manohar**[5], **M. Ajay Kumar**[6] and **T. Anil Babu**[3]

[1] *Department of Physics, BIT Institute of Technology, Hindupur, A.P., India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India*

[4] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

[5] *Department of Materials Science and Engineering, Korea University, 145 Anam-ro Seongbuk-gu, Seoul 02841, Republic of Korea*

[6] *Department of ECE, GITAM Deemed to be University, Bangalore-562163, Karnataka, India*

Abstract: Corrosion is a defect of the material which reduces the life of the electronic device or any other devices which are fabricated with metals and alloys. Generally, using polymer coatings, the corrosion is decreased comfortably in large devices. In this chapter, we highlighted the corrosion in electronic gadgets and printed electronic circuit board. Furthermore, we discussed corrosion of electronic printing board with the possibilities, types of the corrosion as well as protective phenomena.

Keywords: Corrosion, Epoxy coatings, Galvanic Corrosion, Printed Electronic Board Assembly, Surface Mount Components.

1. INTRODUCTION

The usage of electronics and peripherals increased over the last two decades. The electronic printing device contains a greater number of transistors and its derivatives with the most convoluted circuit's arrangement for the sake of high functionality. Mobile phones are one of the examples of the high functionality and complexity in the arrangement of electronic components such as smart cameras, GPS systems, and various application support working components. In general, the usage of integrated circuits in electronic gadgets is simple, but fabrication involves an assembly of many metals and other properties like durability and

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering, Anantapur-515002, Andhra Pradesh, India; Tel: +91-81211 27157; E-mail: sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

reliable nature in all environmental aspects. On the other hand, the electronic industries provide significant applications in world technology irrespective of the environmental situation. However, the factories or companies of manufactures of electronic components could not take corrosion resistance conditions seriously. Usually, the electronic devices contain PCBA (printed electronic board assembly) as a heart. Environmental conditions like humidity (percentage of water in the atmosphere) can be provocative for the generation of a layer of water on the PCBA, which results in the corrosion generates in PCBA. This corrosion can influence the functional operation decrement extremely of PCBA [1 - 3]. The corrosion executes problems in the integrated function and multi-material predictions of PCBA in a specified electronic device. The multi-material means the device which includes a group of materials like plastics, metals, polymers, ceramic material, and complexes of different materials. Moreover, among all the materials, the main class of materials was metals and its composites. The reaction of humidity with PCBA selects those materials which were used in the PCBA of the device.

In the present days, the materials mainly used in the PCBA are noble gold, silver, tin, aluminium, nickel, copper, lead and tin. Not only these materials but also the above metal combinations are used for the layer of circuit coatings in the board. The electrical system contains both electronics (materials which control the flow of electricity) and electrical components, which include non-electrical systems such as switch, *etc* [4 - 6]. In the development of electronic devices starting from volume tube, now we use transistors which were fabricated through solid-state materials. These types of transistors make possible to electronics with comfortable size and usage in the electronic world every day. Therefore, it must be continued in the coming days. The electronic industry encountered many problems for comfortability in the origin of computers to end of kitchen devices through the development of electronics. Thus, the corrosion due to the different kinds of materials used in the electronic devices became more problematic than those materials having different states of environment [7]. In the periodic table, many elements and their complexes are used to fabricate resistors, integrated circuits, and printed board in every industrial electronic company [8]. Fig. (**1**) shows the corrosion on the circuit board.

The materials used in electronic devices face different types of corrosion. The interaction of corrosion depends on the kind of materials and metals such that some materials get corrosion slowly while some other materials get it spontaneously [9, 10]. In the group of electronic materials, the efficient material is gold. This is used at contact area in PCBA and layers of some other quickly reactive materials due to its non-reactive nature. That is why, gold is one of the costly materials and lasts for a long time. It is a well-known fact that the formation of oxide layers is defined as corrosion when reacted under certain environmental conditions. The non-reactive nature of gold restricts the oxide formation, while corrosion-efficient materials like aluminum can offer chances of oxide formation easily [10]. Generally, the circuit can be created with the help of one or two and more different metals. If the circuit is created with the help of two or more metals ions, it moves faster than the normal electronic circuit. Those different metal contacts generate salts and oxides. This process generally is referred to as galvanic corrosion. This is one of the largest problems among the corrosions of different materials and their interaction with different environmental conditions like humidity, moisture, and temperature. The galvanic corrosion generally happens only in the electrolyte, and it needs some moisture to start. This moisture can come in the water spray or relative humidity in the atmosphere. This relative humidity efficiently affects the occurrence of galvanic corrosion, and it isn't easy to control. These situations are hazardous where the electronic device is working. In addition, the temperature generated at machinery makes it dried surrounding the electronic device. Apart from the moisture, the air is also a second important factor for improving corrosion because the air contains many gases (nitrogen, sulfur components) reacted with elements and increase corrosion. Chloride, sulfur, and nitrogen ions supply the enormous corrosion of aluminium and its composites. The corrosion in big devices like ocean ships and containers may have this galvanic corrosion effect periodically due to the high dampness. The increase of temperature simply increases the rates of all these reactions [11]. The impact methods can protect from the corrosion of the electronic equipment from the small to bimachineries. The main factor in controlling corrosion is temperature. If we control the temperature variations, we can easily monitor corrosion variations.

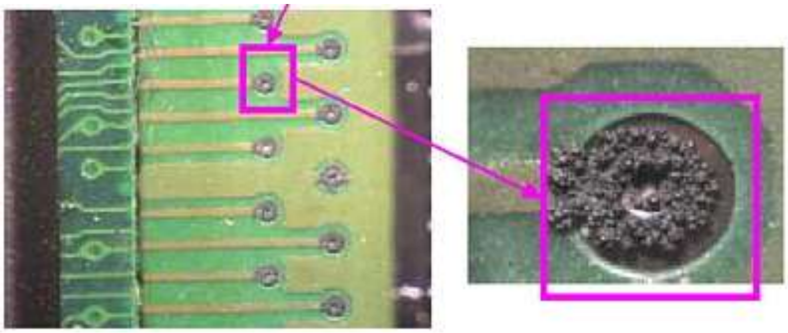

Fig. (1). Corrosion on the circuit board.

CHAPTER 4

Corrosion of Polymer Materials

U. Naresh[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3,4], **A. Manohar**[5] and **T. Anil Babu**[3]

[1] *Department of Physics, BIT Institute of Technology, Hindhupur, A.P., India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University , Bangalore - 562163, Karnataka, India*

[4] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

[5] *Department of Materials Science and Engineering, Korea University, 145 Anaro, Seongbukgu, Seoul 02841, Republic of Korea*

Abstract: The technology is growing very fast in the world with the expansion of novel functional materials. These novel materials are the backbone for technology development. Whereas the lifetime of materials is decreased due to environmental aspects such as the breakdown of a chemical bond with the oxidation process. Usually, it may be called corrosion. In this chapter, we reviewed some corrosion aspects like corrosion types and causes of corrosion. In addition, it also discusses protective materials like conductive polymer and its composites, such as conducting polymers mixers of magnetic materials and graphene additives.

Keywords: Conducting, Dealloying, Fretting, Hygroscopic Contaminants, Monomers, Nanoparticles, Polymers.

1. INTRODUCTION

It is a well-known fact that the corrosion is treated as the morphological imperfection of metal-based materials because of the oxidation process. Generally, polymers or some lubricants are used to protect metals from corrosion. The corrosion usually happens on the polymers, and rubber materials. This type of corrosion is very different than natural corrosion. Because, other corrosions can be identified easily, whereas the polymer corrosion is not possible to identify quickly. The probable chance to find corrosion in polymers is the loss of

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering, Anantapur-515002, Andhra Pradesh, India; Tel: +91-81211 27157; E-mail: sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

mechanical properties of the materials. That is, if the mechanical stress is applied to the corrosion polymer materials and their chemical environment, those materials immediately undergo creeping or cracks on the surfaces. Generally, chemical reaction and physical interactions are the two major types occurred in polymer materials.

2. CHEMICAL REACTION

The polymer materials are non-crystalline materials having the mixture of molecular series of carbon, oxygen, hydrogen. As the materials are exposed in the environment, the chemical reactions take place leading to the corrosion. If the reaction takes place under the heat or far infrared and UV-Visible radiation, the polymer chain gets breakdown. In the environment, the ozone and water make hydrolysis process of polymer monomers. Therefore, it leads to the breakdown of chemical bonds. The difference between breakdowns of chemical bond is due to inflammation or dissolving chemical elements without variation of structure.

Excess of reaction resistance is required on the molecular structure of the polymer, whether they are unstructured or partially crystalline. Semi-crystalline materials are more resistant than amorphous polymers. Physical contacts on polymers happen mainly due to the environment. Hence, the materials undergo dissolving or swelling because of chemical reactions or leakage of polymers. However, the interaction depends on the penetration of additives into polymer substances. More generally, organic polymers usually affect many physical interactions, whereas some of the materials like strong acids and base reactance may cause the breakdown of the polymer materials. Interestingly, all the conducting polymers acquired impressible importance in the field of coating technology, as they show very good corrosion resistance properties. Especially polyaniline coatings are the considerable choice for protecting metals. The blend type polyaniline additives are one of the best choices to protect metals from corrosion, as they provide many benefits [1 - 4]. The polyaniline emeraldine salt is the most thoroughly investigated and studied polymer.

3. CAUSES OF CORROSION

3.1. Moisture

The printed electronic board assembly surface gets corrosion mainly due to humidity interaction by creating a water layer. There are several ways to react humidity with PCBA. The humidity interactions with metals or solid-water interactions can be classified into surface interactions, condensed water interactions and water internalized into the solid. The humidity interactions can be classified as deliquescence, adsorptions, capillary condensations, absorption of water, and formation of the layer. Among all the types, deliquescence, adsorption, and capillary condensation are the important interactions of PCBA. Of course, the PCBA material, architecture, surface contaminations are also dependable parts for corrosion. Water penetration through the absorption modification is a part of properties of PCB laminated or bulk components and, therefore, equipment causes internal degradation [5].

3.2. Water Absorption

The water absorption is usually caused due to penetration of wetness in PCBA and further it forms the layers of dampness. The moisture ingress prior to soldering can cause delamination at the later stage of manufacturing. An example of this is reflow soldering of the surface mount components (SMCs). In addition, as the electronic device is warmed up, water absorption affects the thermal properties of PCB materials. The dielectric property of laminate is increased due to interface leakage. Hence, the efficiency in multi-layer PCBA is also increased [6]. Generally, the capacitance of the capacitor changes the electronic board laminates and the moisture content in the laminates follows a proportionality relationship for the moisture measurement [7 - 9]. At the time of assembly process, the circuitry is confined to interacting the solder by applying a solder mask, thereby covering most of the laminate surface.

3.3. Water Adsorption by the Hygroscopic Contaminants

Absorption by water-soluble ionic residues and contaminants on the surface of the PCBA affects the surface insulation resistance (SIR). The number of adsorbed molecular layers of water increases with the relative humidity. As the ambient relative humidity meets a cutoff value of relative humidity, the deliquescence (conversion of solid into saturated solution it is generally referred as phase transformation and it depends upon the atmosphere characteristics, that is temperature) will be formed in the PCBA. At the stage of relative humidity of deliquescence, the moisture may be transformed as temperature dependent solid.

4. TYPES OF CORROSION

4.1. General Corrosion

This is also called uniform corrosion. It is well recognized corrosion, and the developed synthetic and chemical reactions are due to the fragile of the uncovered surface. Hence, the metal gets apart of degradation. General corrosion

CHAPTER 5

Corrosion and Corrosion Protection in Drinking Water Systems

T. Vidya Sagar[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3, 4], **D. Baba Basha**[5] and **T. Anil Babu**[3]

[1] Department of Physics, S K University, Anantapuramu-515003, A.P., India

[2] Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India

[3] Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India

[4] Department of Physics, The National College, Bagepalli-561207, Karnataka, India

[5] Department of Physics, College of Computer and Information Sciences, Majmaah University, Al'Majmaah, Saudi Arabia

Abstract: In this chapter, we discussed the corrosion and corrosion protection in drinking water systems. The corrosion of the drinking water distribution system (DWDS) basically depends on the pH of water, the hardness of water, alkalinity of water, buffer intensity, total dissolved oxygen, and inorganic carbon. The indices LSI and LI are discussed. The inhibitor effects of phosphorus and sulfate are discussed. The effect of the presence of metal ions like Zn, Mn, Cu, Cd and Pb on DWDS is discussed. The temperature effect, microbiological induced corrosion and galvanic corrosion processes are briefly presented. The stagnation of water and leaching of Cu, Zn in commonly used DWDS is discussed with the toxicity of iron-based deposits in DWDS. Also, the protection of DWDS from copper pitting is presented. Some of the protection methods to reduced corrosion in steel pipes, Al and Mg-based alloys are also discussed.

Keywords: Corrosion, Drinking Water Distribution Systems, Toxicity Effect.

1. INTRODUCTION

Corrosion is a series of chemical reactions of metals or alloys with their surrounding environment. The reactions of these materials present in the drinking water distribution system such as iron, steel, or their alloys to the different environmental conditions like temperature, wetness, dryness and the characteristics of water pH, salinity, acidic nature, microbiological activity,

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering, Anantapur-515002, Andhra Pradesh, India; Tel: +91-81211 27157; E-mail:sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

presence of heavy metals such as lead, cadmium, arsenic, *etc*., lead to the corrosion of drinking water systems. Sometimes, these contaminants get dissolved in water leading to health disorders. This results in the change of water quality such as its color, odour, pH, total dissolved solids (TDS), dissolved oxygen (DO), increase in microbiological activities, *etc*. As most diseases are mainly water-borne, it is essential to study the corrosion and corrosion protection in common drinking water systems to provide healthy and pure drinking water to mankind. The corrosion in these pipes can lead to a decrease in the lifetime of supply pipes, a reduction in the supply capacity, and loss of water quality. Corrosion will be present, where two dissimilar metals are contacted under suitable conditions, either directly or indirectly. The corrosion in drinking water distribution systems generally depends on the types of metallic materials used, the quality of water supplied in them, the temperature of the environment, *etc*.

This corrosion will reduce the quality of drinking water to a major extent. The corrosion in DWDS mainly depends on the rate of the flow of water, acidity and alkalinity, the temperature of the water, stagnation of water in the supplied water in the pipes, dissolved O_2, CO_2, presence of rust, sand, sediments, byproducts, salts of chlorides and dissolved sulfates. In addition to this, pitting corrosion also takes place due to the defects in metal pipes. Cast iron and steel pipes occupy a major part in the world's largest supply of drinking water distribution. The main chemical reaction regarding corrosion of cast iron pipes is the conversion of metallic iron (Fe) into ferrous to ferric hydroxides with the reaction of O_2. This results in the release of "red water" finally. The corrosion of iron is quite complex in nature and leads to scale formation, byproduct release, turbidity, and staining. The areas with different concentrations of oxygen and metals can lead to the acceleration of corrosion by biological things [1 - 6]. In this chapter, we would like to present the various factors causing corrosion in DWDS and methods to protect them from corrosion.

2. EFFECT OF PH ON THE CORROSION OF DWDS

The pH of water should be monitored at every stage of drinking water distribution system. If the pH value is small (<3.0), the corrosion becomes high. However, the pH value should be less than 8, as greater pH leads to irritation of the eyes of humans and increases the contamination of chlorine [6]. Increase in pH value leads to weight loss as well as reduced iron concentration levels [7]. The metals like Fe, Pb, Al increase the rate of corrosion when pH of water in DWDS is low [8]. Drinking water parameters such as pH, chloride and sulfate concentrations can provide a measure of corrosivity of the drinking water in the distribution system. Many metals such as lead, iron and aluminium exhibit an increase in corrosion rates in low-pH (less than 5) solutions, when pH is greater than 5, protective layer is formed, which reduces the corrosion due to these metals [9].

3. ALKALINITY AND LANGELIER SATURATION INDEX (LSI)

The mild steel increases the corrosion rates due to chloride and sulphate ions, where the pH value is very low. But in this case, pitting is observed due to the presence of oxygen ions. The normal value of alkalinity of drinking water systems is in the range 100 – 200 mg/L as calcium carbonate [9]. Red water is observed when alkalinity is greater than 60 mg/L as $CaCO_3$ [10]. As the drinking water distribution systems are exposed to environmental effects such as air, pitting is observed under these areas. The presence of oxygen increases the rate of corrosion in this case. But there is no significant effect of calcium or carbonate ions compared to sulphate and chloride salts in water. As the alkalinity is much greater than the sulphate and chloride ions, pitting effect is more within the pH values of 6.5-7 and less once the pH values lie between 8 to 9. As the alkalinity ratio is less than 5, the corrosion rates are increased in drinking water. Low alkalinity and high pH of water leads to the copper pitting corrosion. Larson (1971) stated that the stability of saturation by calcium carbonate is a measure of the quality of water. The Langelier Index can be used to determine this mechanism [10]. We can observe the formation of a protective layer on the pipes, as the water having optimum levels of calcium carbonate indicates a positive Langelier Index. This phenomenon is reversed for a negative Langelier Index, and hence corrion rate is accelerated [11].

4. BUFFER INTENSITY

It is also known as buffer capacity. When the intensity of buffer is high at a constant temperature, the alkalinity decreases the corrosion rate of mild steel in the pH range (6-9) [12]. The loss for cast iron occurred once the buffer intensity reaches a pH 8.4. This is occurred due to the increase in the buffer intensity and further reducing the changes in pH due to corrosion reactions. But at the higher ionic strength and increased conductivity in buffer intensity at different pH levels, the corrosion rates are not decreased [13].

5. TOTAL DISSOLVED INORGANIC CARBON AND ORGANIC CARBON

The presence of inorganic carbon as carbonates, bicarbonates, CO_2, and carbonic acid leads to the formation of carbon films on the surface of the metals. This

CHAPTER 6

Corrosion in Reinforcement Cement Concrete

B. Venkata Shiva Reddy[1, 2], **N. Suresh Kumar**[3], **K. Chandra Babu Naidu**[1,*], **D. Baba Basha**[4], **M. Balaraju**[5] and **T. Anil Babu**[1]

[1] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[2] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

[3] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[4] *Department of Physics, College of Computer and Information Sciences, Majmaah University, Al'Majmaah, Saudi Arabia*

[5] *Department of Chemistry, PSC & KVSC Govt. Degree College, Nandyal, Kurnool-518502, A.P., India*

Abstract: Corrosion is an electrochemical reaction initiated by many factors like the ingress of chloride particles and carbon particles. The electrons can move in the steel rebar and the ions can move in the concrete, which acts as an electrode leading to corrosion. The rate of corrosion can be mitigated by the addition of corrosion inhibitors into the concrete. The corrosion increases the volume of rebar and hence, cracking of concrete takes place. The cracking of concrete can be mitigated by the addition of fibers and bacteria into the concrete. The bacteria can produce calcium carbonate, which helps in the self-healing of cracks in concrete. To examine the damage of the reinforcement in the concrete, X-ray microcomputed tomography is employed without wasting of testing sample.

Keywords: Bacteria, Chloride and Carbon Particles, Corrosion, Electrochemical Reaction.

1. INTRODUCTION

Cement is the general name for powdered materials that initially have plastic flow when mixed with water. But they form a solid structure after several hours with varying degrees of strength and bonding properties. The compositions of cement

---

[*] **Corresponding author K. Chandra Babu Naidu:** Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India; Tel: +91-9398426009; E-mail: chandrababu954@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

are Al_2O_3, SiO_2, SO_3, K_2O, CaO and Fe_2O_3. The corrosion in reinforcements of cement is a common problem, but a slow process. Corrosion is a process of electrochemical reaction that takes place due to the flow of charges like ions or electrons. The industrial material like steel and iron get corrosion as they are not naturally available materials but occurs in the form of ore. The steel, like many materials except platinum and gold, is unstable under atmospheric conditions and revert into its natural state with the release of energy-iron oxide or rusting. This process is called corrosion. Chloride induction into steel is a common cause for corrosion in reinforcement structure and dissolution of iron. This leads to the formation of iron oxides. The corrosion takes place as the chloride value is greater than the threshold chloride value. However, corrosion initiation depends on many factors like quality of steel or concrete interface, the chemistry of the pore solution, potential of the steel and the orientation of the reinforcement to the concrete casting direction, also including macro factors such as macro pores, air voids and cracks [1]. The corrosion profile reinforcement can be characterized with impressed current densities by X-ray micro-computed tomography (XCT). This is a non-distractive method than any other methods. It is impossible to nondestructively monitor with the process of the gravimetric method and 3D scanning. Even though electrochemical methods (Linear polarization resistance and electrochemical impedance spectroscope) are nondestructively tested, they cannot be used to visualize the morphology of reinforcement. The impressed current density may be varied depending on the morphology of the reinforcement and concrete cracking.

The XCT test is conducted to trace accelerated corrosion with the impressed current. The chemical compositions of reinforcement are C, Si, Mn, P, S, Cr and Fe [2]. In railway engineering, shotcrete (spay concrete) is used in railway tunneling, in which the steel rods are used as a reinforcement. In the electrified railway system, the train gets electric current by overhead connection to the electric line. Thus, in an electric train, the stray current is developed, which disperses from the current return path, such as running track, surrounding buildings and infrastructure. The reinforcement steel in the shotcrete can pick up the stray current, which leads to corrosion [3]. The reinforcement concretes are built-in railway/highway bridges, high rise buildings and power plants with a target life of more than one hundred years. To get such a long target life, the steel is coated with organic inhibitors and coating to improve the corrosive resistance power. The organic coating provides a shield or physical barrier between the under-laying steel and deleterious elements like chloride elements, moisture and oxygen and restricts the ionic and cathodic areas. The cement polymer composite and the acrylic base is a type of organic coating which is widely used in the construction industry [4]. Incorporation of inhibitors (Fly ash or silica fume) into the concrete also improves the performance of concrete. Silica fumes are more costly than fly ash. Silica fume is more efficient pozzolanic material than fly ash. Fly ash is the by-product of industrial waste produced by the burning of coal combustion in electric power generation [5].

The corrosion is of two types, one is general (uniform) and pitting (localized). The most direct cause for corrosion is a reduction in the reinforcement of diameter of material and cross-sectional area. This reduction is responsible for the structural safety and integrity of the reinforced concrete. If the cross-section depreciation is high, the working stress is also maximum in the reinforcement. The corrosion produces insoluble bi-products commonly known as rusting, which increases more volume 3 to 8-fold than that of the original volume of the material used. This expansion leads to cracking, spalling and delamination of the concrete cover and bond loss between steel and concrete. This further accelerates corrosion rate and hence reduces the serviceability of concrete [6]. The corrosion rate is directly proportional to the electrical resistivity and inversely proportional to the concrete resistivity. The presence of micro silica and nano silica additives reduces the corrosion rate in concrete [7]. A new type of cement-based composites coral aggregate composites is being used for specific purposes in ocean-going Iceland reefs projects. The coral aggregates are economical and high efficiency. The coral aggregate replaces the natural sandstone in the preparation of coral aggregate concrete. Coral aggregates are composed of aragonite, dolomite, and calcite. The main ingredient is calcium carbonate and a little bit of chlorinated salt [8]. In sea or ocean, the Cl^- decides the durability and strength of the concrete structure of reef. However, the porous structure of coral and Cl^- in seawater leads to the corrosion of reinforcement steel. The apparent chloride diffusion coefficient and surface free chloride concentration are important parameters to assess the diffusion of Cl^- ions and service life of concrete structure [9]. The coral aggregate concrete is made by locally abundant coral reef debris. This is secreted by algae and coral polyps [10].

The magnesium oxychloride cement concrete [MOCC] is an improved form of cement that is ecofriendly and reduces waste resources. This concrete can exhibit the improved energy conservation and reduction of emission. The MOCC is a good halogen resistor without modification and the chemical composition is $MgO-MgCl_2-H_2O$. When steel starts corroding, the dimensional changes can take place in the steel *i.e.,* the cross-sectional area is decreased, the bond between concrete and steel reduces the formation of cracks. Hence, it leads the structural damage. The following methods can be employed for the investigation of steel corrosion:

- Dry and wet cycle test,
- Chloride ion penetration test,

CHAPTER 7

Environmental Cracking of High-Strength Aluminum Alloys

B. Venkata Shiva Reddy[1,2], **N. Suresh Kumar**[3], **K. Chandra Babu Naidu**[1,*], **M. Balaraju**[4] and **T. Anil Babu**[1]

[1] *Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India*

[2] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

[3] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[4] *Department of Chemistry, PSC & KVSC Govt. Degree College, Nandyal, Kurnool-518502, A.P., India*

Abstract: The aluminium alloy is the second-largest alloy being used in the world next to steel. Aluminium exhibits good mechanical strength, resistant to corrosion and lightweight. But due to some environmental variations or conditions, the alloy was found to be prone to cracking. The microstructure cracking is due to many factors like corrosion, mechanical stress, thermal stress, and bacterial adherence. The Sulfate Reducing Bacteria (SRB) is the most active bacterium, which causes rusting. The chloride ions present around the aluminium alloy led to corrosion and the failure of microstructures in the alloy.

Keywords: 3D printing, Alloys, Corrosion, Cracking, Microstructures.

1. INTRODUCTION

An alloy is a mixture of two or more metals mixed in a required proportion. This gives special and improved properties than single metal. Such properties are strength, ductility, malleability, conductivity, resistivity, *etc*., used in industrial sectors. Aluminium alloy is the second-largest industrial material next to steel and has many advantages in engineering materials. In recent context, aluminium-based alloy materials are being manufactured by 3D printing or additive manufacturing [AM] rather than the traditional manufacturing process. 3D printing is preferred due to unlimited freedom design, economical, less time consuming, no wastage of substance, *etc*. [1]. In additive manufacturing, varieties

---

[*] **Corresponding author K. Chandra Babu Naidu:** Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India; Tel: +91-9398426009; E-mail: chandrababu954@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

of methods are being used to print the materials, but in aluminium alloy printing, the preferable method is selective laser melting [SLM]. Anyway, there are common problems in the SLM such as cracking, balling and porosity [2]. Fatigue is one of the most prominent problems associated with structures, as the object is subjected to cyclic load. It is well recorded in many studies that the crack nucleation does not contribute particularly to the total fatigue of the component. Moreover, most of the fatigue life will be in short crack growth rather than long crack. The short fatigue cracks are in the order of 10 μm to 1 mm dimensions. Short cracks are classified broadly into; chemically short cracks, physically short crack, microstructurally short crack, and mechanically short crack [3]. The skin of the aircraft is made up of aluminium alloy, which accounts for 50% of its total weight. The micro-cracks will be taken place due to various external factors like heavy load or stress, temperature, and pressure [4]. Among many aluminium alloys, the cast aluminium alloy (A356Al Alloy) is widely used in automobiles like pistons, engine parts and cylinder heads. In automobile heat engines, cast aluminium can withstand high temperatures, and it possesses high strength to weight ratio and wear resistance.

However, α-aluminium dendrites and interdendritic irregular in Al-Si eutectic (easily melting) regions lead to microstructural defects in the system. To overcome these problems, many approaches are available such as modification of microstructures and friction stir processing [5]. The 7XXX series of aluminium alloys are widely used in military and aerospace sectors. They possess low density, supreme mechanical properties, and outstanding machinability. In 7A99 Al alloy, high Zn and low Cu mixtures were developed with high mechanical strength and low corrosion. But the artificial ageing of the aluminium alloy leads to structural, physical, and chemical changes such as microstructures, mechanical properties, stress, and corrosion cracking. To improve the mechanical properties, the intense grain refinement, and achieving the minimum sub micrometric scale (>1 μm) through severe plasticity [6, 9] are adopted. However, the thin oxide layer is formed around the aluminium alloys, preventing the destructive corrosion process. The 5XXX (Al-Mg) series are more corrosive resistant than 4XXX (Al-Si) and 6XXX (Al-Si-Mg) grades. Anyway, the presence of excess Mg leads to corrosion. Hence, a new grade AA5052 with 2 to 3% of Mg is allowed, which can curb the corrosion. In the AA5052 grade, it is very hard to form a continuous intermetallic phase located at grain boundaries [7].

During the laser welding process in Al-Mg composition alloy, the Mg will be evaporated. This leads to the weld material, and evaporation of magnesium metal can affect the solidification path of the alloy [8]. The equal channel angular pressing (ECAP) can improve the mechanical properties of aluminium alloys like Al-Mg, Al-Cu, Al-Si, *etc*., by means of intense grain refinement. The halide atmosphere around the aluminium alloy leads to pitting corrosion, and the reduction of grain size contributes to the minimization of corrosion. The minimization of grain boundary size leads to the increase in grain boundary density and breakdown of secondary phase particles below the critical size [9]. The minute changes in the service environment account for the major damages in alloyed structures. In 1985, Japan airlines flight 123 prone to fatal with 520 lives due to long-term corrosion fatigues [10]. The temperature, relative air humidity and corrosive media play a crucial role in the aluminium alloy properties. It is found that at lower temperatures below -20ºC, all alloys can exhibit longer fatigue lives and shorter fatigue crack propagation rate (FCGRs). But at room temperature, the alloy exhibits higher strength and fatigue lives decrease. If the temperature exceeds 350ºC, it decreases the strength and increases the oxidation rate. With increasing temperature, relative air humidity decays the fatigue properties of the alloy. This leads to the acceleration of FCGRs of aluminium alloy. In corrosive media like NaCl fog, acid solution and alkaline solution, aluminium alloys are quite sensitive. Thus, the initiation and propagation of micro-cracks take place. In the Na-Cl solution, Cl ions cause severe pitting on the surface [10, 11].

Solidification is one of the causes to get of fracture in alloys, and it is called solidification cracking (SC). Between the solidified weld metal and welding pool, there exists a semi-solid region, that is a mushy zone. Solidification cracking takes place at the end of mushy zone, where some residual liquids can exist in the form of film in a liquid state. The initiation of SC takes place at the terminal solidification stage due to the reasons such as shrinkage, thermal strain, hindered contraction and lack of liquid feeding [12]. However, aluminium alloys are easily prone to cracking during solidification because solid density is greater than liquid density. Further, another problem; the micro-voids are also formed in the brittle secondary phase due to the initiation of microcracks. Thus, lead to a failure in the alloys [13]. During the welding alloys, the microstructural guarantee is important and maintained by friction stir welding (FSW). This exhibits excellent weld efficiency and avoids high heat entry during manufacture. The advanced welding system called Bobbin tool friction stir welding (BT-FSW) is used. The BT-FSW requires back support and particularly suitable in closed structures like pipes and tanks. Of late, semi-stationary shoulder variant (SSuBT-FSW) is the working concept in alloys like Al-Cu-Li [14]. However, the fatigue properties are anisotropic in nature and to scale down the cracking susceptibility, filter metals along with non-matching composites are often essential to adjust the composition of the weld metal in the fusion zone [15]. The ageing factor of alloy also plays a very important role in fatigue and cracking, such as peak aged, over aged, retrogression and re-ageing. The re-ageing alloy exhibits the highest resistance to

CHAPTER 8

Corrosion of Nuclear Waste Systems

K. Ramakrishna Reddy[1], **N. Suresh Kumar**[2,*], **K. Chandra Babu Naidu**[3], **B. Venkata Shiva Reddy**[3, 4] and **T. Anil Babu**[3]

[1] *Department of Chemistry, Reva University, Bangalore 560064, Karnataka, India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[4] *Department of Physics, The National College, Bagepalli-561207, Karnataka, India*

Abstract: In this chapter, the corrosion problems of nuclear waste systems in view of the disposal are discussed. The main form of waste of packages is discussed, ascertaining high-level waste, and the cemented intervening level radioactive waste forms, vitrifying nuclear waste, canister waste forms and nuclear waste glasses. The discussion between the rate of corrosion of all the nuclear waste packages with the nuclear waste disposal concept and the safety measures of the landfill sites is featured. Furthermore, the corrosion of the various kinds of nuclear waste packages and the metallic container for the high-level waste packages are reviewed. In view of the deterioration or dissipation processes, the experimental in-situ approaches, and the exemplary corrosion of nuclear waste and lifetime forecasting are discussed. The major challenge in global research is acquiring data and authentic forecasting for the function over long term periods, as landfill of these kinds of nuclear waste packages must abide safe for very long periods of years.

Keywords: Corrosion Issues, High-Level Waste, Nuclear Waste Forms, Radioactive Waste.

1. INTRODUCTION

Radioactive waste is defined as the material that is contaminated with radioactive nuclide at concentrations greater than a safe level. It does not have any practical purpose. Radioactive wastes are usually by-products of nuclear power generation and other applications of nuclear fission or nuclear technology, such as research and medicine. Radioactive waste is hazardous to most forms of life and the environment. It is regulated by government agencies to protect human health and

---

[*] **Corresponding author N. Suresh Kumar:** Department of Physics, JNTU College of Engineering, Anantapur-515002, Andhra Pradesh, India; Tel: +91-81211 27157; E-mail: sureshmsc6@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

the environment. That is, all waste materials which are radioactive in nature are called radioactive waste. The petrified issue is caused due to the changes in earth's temperature or changes in climate. It is authorized for the use of nuclear energy, such as the non-production of greenhouse gases. In further coming years, nuclear power extensively relies on the management of nuclear waste, produced at various steps of the nuclear fuel cycles. It is believed that the radioactive waste disposal across the world of high-level nuclear waste paralyzes them to a matrix of the solid (glass). The glass can disintegrate many elements existing in the periodic table, and it can be utilized as a medium for waste confinement [1, 2]. Glass is an exactly non-religious compound. All the elements present in the same compound are the main components in the glass consisting of the nuclear waste. With the high percolate resistance of the glass, it is impossible to disintegrate into water. Low percolate character is the required criteria for a solid compound to vitrify nuclear waste.

The poor corrosion inclination will identify the resultant nuclear waste glass. Borosilicate and lead iron phosphate glasses are appraised as a selective solid matrix for high-level nuclear waste [3, 4]. The ultimate disposal of high-level nuclear waste presumes multi-barrier approach. The radionuclide, which is coming from the nuclear active waste glass enters the biosphere. The groundwater encounters the nuclear active waste glass after perforating all the barriers applied for the nuclear active waste glass. The behavior of corrosion of nuclear waste glass always explains opposing percolate in the presence of moisture [5]. Knowing the percolation of nuclear waste, glasses are essential since they treated as a geological warehouse for a large amount of time. To find out directly the corrosion of long run is quite tough using small experiments. But for the performed experiments in laboratory, the long run corrosion can be measured.

The trustworthy disposal of long-living radioactive waste for geological time scale is one of the most important issues in the safety application and acceptance of nuclear energy. The trustworthy disposal involves the development of robust disposal concepts, explaining their safety over the geological chronicles, and knowing the properties of different natural barriers in the topographical warehouse. It took almost 30 years to do research to find performance all over the world into different nuclear waste forms, to study their properties like thermal, radiation, chemical, mechanical, and physical properties related to eventual long-term disposal. The main pattern used to paralyze nuclear waste are cement, bitumen, glass, and, more recently, ceramics and spent fuel. This chapter initiates the corrosion property of some of the major waste forms considered globally for a long period and high-level radioactive waste. High-level radioactive waste is glass, and intermediate-level waste is cement. Both are discussed since these are the most characteristic waste forms examined today. The corrosion of spent fuel is also reviewed since direct disposal of spent fuel is presently being examined in many places globally. The corrosion of the metallic container material is explained as well, as their part is very appreciative to the role of the waste form itself. Both constitute the waste package corrosion property, and it is one of the most predominant properties of the nuclear waste package. It contains the release of the radionuclides into the surrounding repository. Further, it governs to a large extent of lifetime of these engineered barriers in the repository.

The nuclear corrosion of glass of borosilicate in aqueous can be studied. The dissolution of the glass is the huddle of various processes and mechanisms. Dissolution began with the hydration of glass by the diffusion of water into the glass matrix. Further, the ion exchange process among the protons available in the earth crust and base metal in the production of glass occurs. The dissolution of glasses can be done by reacting with water since the ionic covalent bond is the most soluble element of the glass matrix.

2. POTENTIAL CORROSION ISSUES IN NUCLEAR WASTE PACKAGES

2.1. Description of Typical Waste Packages

The radioactive waste is generated in various extents of the nuclear fuel cycle. In the operation of mining of uranium ore, fuel generation, the operation of the nuclear power plant, handling of the spent nuclear fuel, and dismantling and decommissioning of the nuclear power plant at the end of its lifetime. Nuclear waste is also produced in research laboratories, hospitals, universities, chemical industries, *etc*. All these various types of nuclear wastes are subsequently handled (conditioned, immobilized) in such a way that the resulting waste packages can be safely stored and eventually disposed in surface or geological disposal sites [6]. The most popular kinds of radioactive waste packages and in those packages, the corrosion issue is important. Those are the corrosions of vitrified high-level waste, spent uranium oxide fuel packages, and cemented waste packages.

2.2. Vitrified High-Level Waste

Vitrified waste form immobilizes the sludge issuing from the reprocessing of spent fuel, and contains fission products, actinides, and activation products. Through a verification process, these highly radioactive solutions are incorporated in a homogeneous borosilicate glass matrix. In the French AREVA R7T7 process, for example, the glass is poured into stainless steel canisters of 134 cm height and 43 cm diameter. In that process, the radioactivity inventory per waste package is

CHAPTER 9

Microbiologically Influenced Corrosion

K. Ram Mohan Rao[1,*], **K. Haripriya**[2], **P. Banerjee**[3] and **A. Franco**[4]

[1] *Department of Chemistry, GITAM Deemed to be University, Visakhapatnam 530045, Andhra Pradesh, India*

[2] *Department of Anaesthesia (prev.), MIMS Medical College, NTR University, Vijaywada, Andhra Pradesh, India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore Campus, Visakhapatnam 530045, Andhra Pradesh, India*

[4] *Instituto de Física, Universidade Federal de Goiás, Goiânia, Brazil*

Abstract: Microbiologically influenced corrosion (MIC) is the subject of concern in various fields like industries related to healthcare, marine, petroleum, oil, *etc*. An attempt is made to present MIC and underlying mechanisms. Cathodic depolarization theory along with the other mechanisms supporting MIC caused by sulfate/nitrate-reducing bacteria is the focus of this chapter. Another important aspect of preventive and mitigation measures of MIC is concerned.

Keywords: Anaerobic, Biofilm, Mechanisms, Microbiologically Influenced Corrosion.

1. INTRODUCTION

Microbiologically Induced Corrosion (MIC) is one of the major problems affecting the economy and ecological safety of various sectors that rely on steel structures. MIC is known to be caused by different types of bio-organisms, *e.g.*, bacteria, algae, and fungi. It causes a significant loss of materials and adds to the cost of damage due to corrosion. Microbes colonize on the surface of materials resulting in the formation of biofilms that are responsible for the infections and microbiologically influenced corrosion (MIC). Generally, multiple organisms are responsible for the formation of a biofilm or outgrowth on the structure causing localized corrosion. The cause and progress of MIC are not clearly understood, which vary in different environments like oil transmission pipelines, marine environment, *etc*. Axelsen and Rogne (1998) first identified MIC more than a

---

[*] **Corresponding author K. Ram Mohan Rao:** Department of Chemistry, GITAM Deemed to be University, Visakhapatnam 530045, Andhra Pradesh, India; Tel: +91- 91138 54549; Email: rammohanrao.k@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

hundred years ago [1]. It was first defined by Videla in 1996, and according to him, "MIC is an electrochemical process in which the microorganisms are present to initiate, facilitate and accelerate the corrosion reactions" [2]. Industrial areas like the healthcare industry, marine, oil and gas industry are affected seriously by MIC. Numerous other areas like water utility, *etc*., are affected severely. According to Flemming (1996) and Videla (2002), MIC is responsible for the leakage of pipelines and the plugging of injection wells causing loss of production and safety issues [3, 4]. Watkinson *et al*. (1984) explained that the condensed water collected at the bottom of the fuel tanks or pipes is responsible for microbial growth forming sediments, sludge, and slime. These are the elements that cause fuel deterioration and corrosion under the biomass produced [5].

Gaylarde *et al*. (1999) and Dzięgielewski *et al*. (2009) showed that fuel used in aviation and diesel fuel is prone to microbial growth because of the use of carbon microorganisms from C10-C18 hydrocarbon chains. At the interface of fuel and water, the nutrients and water are sufficient for the microbial activity and proliferation to take place, which results in the formation of biofilm. The colonization also takes place at the bottom and the surfaces of tanks and pipelines. At the bottom level of sludge and sediments, the obligate anaerobes, for example: sulfate-reducing bacteria (SRB), grow mostly in the anoxic zones, whereas the fuel phase contains only the aerobic microbes [6, 7]. In fuel turbidity, bottom sludge and sediments, unpleasant odour is caused by microbial contamination. The contaminants *via* distribution and transport systems pass to several locations. Further, they form the metabolic byproducts. Filter plugging, pinhole leaks of the pipeline systems and tanks are due to MIC, which is an electrochemical bio-corrosion led by the metabolites of the sulfate-reducing bacteria [8]. Biodiesel is a renewable source and used as an alternative source of fuel, which is non-toxic and contains the Fatty Acid Methyl Esters (FAME) as the main constituent and is more biologically active. The final blend of biodiesel is found to be contaminated by microorganisms [9 - 11]. It is found that not only sulfate-reducing bacteria (SRB) are responsible for MIC, but several other microorganisms are also responsible, *e.g*., acid producers, general aerobic bacteria, iron oxidizers, iron reducers, manganese-oxidizing bacteria, methanogens, *etc.* [12]. Biomedical implants and corrosion are the subject of research for prolonging the life of implants and the cost of their replacement. For example, dental, cardiovascular, orthopaedic implants, *etc*., are made up of stainless steel. The body fluid leads to corrosion of these stainless-steel implants, and the ions released due to corrosion are toxic [13]. Microorganisms are another reason for corrosion which live on the surface of body implants and cause infections. For example, implants fail most often by pitting and crevice corrosion [13 - 17]. For the body implants, AISI 304 and 316L stainless steels are the commonly used alloys that are known to be adversely affected by *P. aeruginosa*. It is found that in biologically active corrosion or microbiologically influenced corrosion, the major role is played by the accumulated microorganisms and the resulting biofilm on the surface of the materials. The role of biofilms in the mechanism of MIC is important to know how corrosion occurs on the surface of the materials and also how to combat or minimize corrosion.

2. A BRIEF HISTORICAL PERSPECTIVE

The first observation that microbially influenced corrosion occurs in metals was by Garett in 1891, who found that the lead sheathed cables undergo corrosion by bacterial metabolites [18]. In the year 1910, Gaines observed MIC and reported the involvement of bacteriogenic sulfur in corroding the internal and external water pipes [19]. Later, Ellis and Harder, in 1919, proved the presence of iron and sulfur bacteria in the deposits [20]. Until 1934, it was remained to unfold that why the underground structures undergo corrosion even though there is no stray current. Then in 1934, Kühr and Vlugt [21] studied graphitization of cast iron in anaerobic soils and found the anaerobic iron corrosion and sulfate reduction to form iron sulfide. Based on the observations, they proposed the first theory based on the bacterial depolarization of local cathodes with the involvement of anaerobic sulfate reducers. Some other groups accumulated the findings to emphasize the bacterial involvement of anaerobic sulfate reducers in inducing MIC [21 - 28]. In 1949, Skybalski and Olsen proposed mechanism that the aerobic MIC is followed by the formation of oxygen concentration cells due to the formation of tubercle [28]. Later, this mechanism was extended by Uhlig in 1953 [29], and the characteristics of steel were studied in the 1960s by other groups [29 - 38]. Iverson *et al*. [38] concentrated on the corrosion of steels by sulfate-reducing bacteria (*e.g*., Desulfovibrio species).

Since 1980, increasing attention is drawn by the industrial sector and many MIC related problems are studied by several workers throughout the world. The evidence is the existing literature on the complex interaction of the metal-biofilm interface and microorganisms and the material characterization [39 - 43]. In the 21st century, the work was devoted to the characterization and analysis of complex microbiological organisms. It was found that in the marine and petroleum reservoirs, the SRB is not the sole culprit, but other microorganisms, *e.g*. those found in industries, also influence MIC [44 - 46]. Some other microorganisms later found were nitrate-reducing bacteria (NRB), iron-oxidizing bacteria (IOB), sulfur-oxidizing bacteria, archaea, methanogens, *etc*. [47, 48]. It is shown by some groups that some of the microorganisms help to reduce corrosion. In the year 2009, Videla and Herrera observed the corrosion inhibition to be induced by microbiological organisms like iron-reducing bacteria [49, 50].

CHAPTER 10

Power Plant Corrosion

S. Ramesh[1,*], N.V. Krishna Prasad[1], N. Suresh Kumar[2], K. Chandra Babu Naidu[1,*], M.S.S.R.K.N. Sarma[1], K. Venkata Ratnam[3], H. Manjunatha[3], B. Parvatheeswara Rao[4] and **T. Anil Babu[1]**

[1] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Chemistry, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[4] *Department of Physics, Andhra University, Visakhapatnam- 530003, India*

Abstract: Corrosion is recognized as a serious problem in power plants that generate electricity. Many power plants generating a huge amount of electricity are needed to be taken care of it. Otherwise, these will cause a serious damage to human life. Corrosion gives rise to wastage of material in huge quantities, failure of tubes, leakage of tubes, sudden shutdowns as well as a reduction in the lifetime of components. Also, it reduces the thermal and electrical efficiency of a power plant to a maximum extent leading to minimum maintenance, outage, and replacement of cost. In understanding this problem, the present chapter illustrates the corrosions that take place in the power plants and preventive measures to be taken to avoid huge destruction to the life on the earth and to the environment. This, in turn, reduces the maintenance cost and damage to the human life.

Keywords: Corrosion, Environment, Erosion, Hot Corrosion, Thermal Spraying.

1. INTRODUCTION

In general, it is a well-known fact to the majority of people that corrosion is nothing but rust. "Rust" is a name which is likely to be reserved for iron, whereas corrosion refers to a natural process of converting a refined metal into a more chemically stable form such as hydroxide, oxide, or sulfide. It is a process of continuous eradication of metals due to chemical reaction and/or electrochemical reaction with their surrounding environment. This can also take place in materials

---

[*] **Corresponding authors S. Ramesh and K. Chandra Babu Naidu:** Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India; Tel: +91- 90000 00664; E-mails: sramesh664@gmail.com and chandrababu954@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

that are not metals, which include ceramics or polymers; the term "degradation" is more common. It is a known fact that corrosion degrades the useful properties of materials like strength, appearance and permeability to liquids and gases. Many alloys and metals show a tendency of merging with oxygen and water contained in their surrounding environment and come back to their stable state. Steel and iron generally interact with their environment to return to their stable oxide states. Hence, corrosion engineering can be treated as the field devoted to the control as well as prevention of corrosion. Like natural disasters like earthquakes or changes in weather, corrosion leads to expensive and dangerous damage to automobiles, drinking water systems, home appliances, gas lines, buildings, bridges, and power plants [1]. Throughout the world, the major production of electricity has happened from thermal power plants, where the water is boiled with the help of coal and the generated steam. This steam gets condensed and returns to the boiler by passing through the exit end of the turbine having lower pressure [2].

The development of more advanced electrical devices requires electrical power for the running of a device. It is made energy source compulsory in contemporary industrial societies. Statistical estimation shows that almost 70 percent of electricity production is from fossil power plants, while 15 percent production is from nuclear power plants and 12 percent is from power plants of the hydraulic type, and the remaining production is from other energy sources in developed countries like the United States of America. So, most countries depend on fossil fuel power plants for energy generation [3].

The fossil fuels involve coal, oil, and natural gas. Coal is a natural fossil fuel which can be extracted easily from the earth's crust compared to oil and gas. Coal is a combustible black or brownish-black sedimentary rock formed as rock strata called coal seams. Heat is generated by burning fossil fuel while one-fourth of the primary energy of the world and two-fifth of the world's electricity is produced by coal supplies. Many of the industries which can manufacture iron and steel and also power plants burn coal. Coal is reported to be a contaminated fuel that contains varying amounts of sulphur , hydrogen , oxygen and nitrogen. It is also called ash and is said to have a complex nature [4]. The amount of coal used in Indian power stations has almost a very high amount of ash (50 percent) that contains hard quartz belonging to abrasive mineral species (15 per cent), which increases the coals erosion propensity [5]. Literature indicates that deposited materials on the fireside that belong to gas turbine surfaces and corrosion leading to many crucial problems. Power plant corrosion leads to continuous and prolonged maintenance, enhancement in operation cost, reduction in efficiency and constitutes risks in terms of safety to workers. Prevention of corrosion is very crucial in order to enhance power generation equipment. This means that the coating for protection should be used for establishing a successful installation of insulation.

2. TYPES OF POWER PLANT CORROSION

1.1. Oxide Corrosion

This is also called dry corrosion referring to an electrochemical process that takes place on metal surface due to an oxygen molecule dissolving in water. In other words, a chemical change in which valence electrons are lost from the atom. If lagging is not installed properly, or if a failure of the protective surface coating takes place or if it is not at all applied, this type of corrosion occurs. Fig. (**1**) shows the corrosion in iron [6].

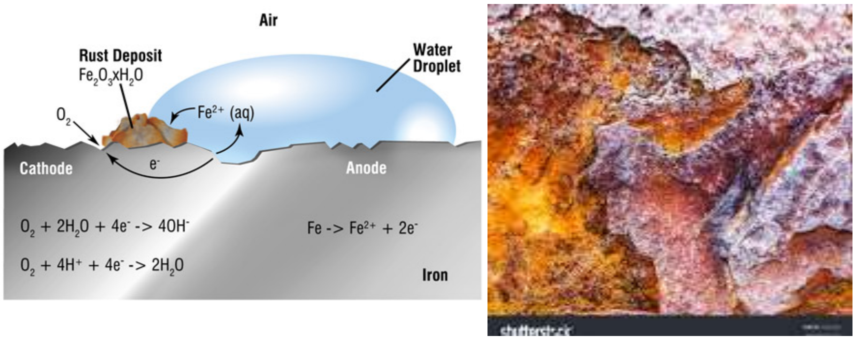

Fig. (1). Rust corrosion of Iron metal oxide [6].

Oxidation Reaction: $Fe \rightarrow Fe^{2+} + 2e^-$

$$Fe^{2+} \rightarrow Fe^{3+} + 1e^-$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH$$

The ferric ions combine with oxygen to form ferric oxide and are hydrated with variable amounts of water. In terms of Layman.

Iron + Oxygen + Water = Rust (Hydrated Iron Oxide)

2.2. Galvanic Corrosion

This corrosion occurs due to contact of two dissimilar metals giving rise to an electrical reaction which in turn leads to corrosion. The difference in electrical

CHAPTER 11

Corrosion in Chemical and Fertilizer Industries

N.V. Krishna Prasad[1,*], S. Ramesh[1], K. Chandra Babu Naidu[1], M.S.S.R.K.N. Sarma[1], K. Venkata Ratnam[2], H. Manjunatha[2] and **B. Chandra Sekhar[3]**

[1] *Department of Physics, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[2] *Department of Chemistry, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[3] *Vignan's Institute of Engineering for Women, Visakhapatnam- 530003, India*

Abstract: Any country's economy and its development primarily depend on its infrastructure apart from existing natural resources in that region. The infrastructure mainly refers to irrigation system, buildings, roads, bridges, airports, transport, education and industries located there. Here it is noteworthy that all these mentioned infrastructures will be corrosion affective which may undergo degradation and deterioration processes. Corrosion is an unavoidable problem that mainly impacts industrial environment. Anthropogenic activity worldwide leads to enhancement of atmospheric pollution which indirectly accelerates corrosion in the form of rust, water pollution. Major industries in any country relate to chemical and fertilizers. India is country with dense population and developing industrially at vast rate. Chemical industry includes companies producing industrial chemicals in which raw materials like water, air, oil, natural gas, minerals and metals converted into seventy thousand products of different type. Indian statistics for the year 2018-19 indicate a production of major petrochemicals and chemicals at 27,847 MT whereas 27,735 MT during 2017-18. In this chapter, we mainly focus on corrosion related to chemical and fertilizer industries, impact of corrosion on their efficiency, corrosion controlling methods and their interrelated phenomena if any.

Keywords: Chemicals, Corrosion, Fertilizers, Industry.

1. INTRODUCTION

Deterioration of a given material on reacting with its surrounding environment is known as corrosion which is a process of converting a refined metal naturally into a hydroxide, oxide or sulfide. It gradually destructs metals by undergoing electrochemical or chemical reaction with surrounding environment [1].

---

[*] **Corresponding author H. Manjunatha:** Department of Chemistry, GITAM Deemed to be University, Bangalore-562163, Karnataka, India; Tel: +91- 88611 58964; E-mail: hanumanjunath80@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

Corrosion is a continuous process and every metal wherever used undergoes some form of corrosion. Corrosion in gas and oil industry is due to water, hydrogen sulfide, carbon dioxide and other existing microbiological activities. If not controlled corrosion in industrial sector may lead to serious problems. Corrosion is a problem of danger and also expensive. Corrosion leads to collapse of bridges, buildings, leakage of oil pipelines and chemical plants, *etc*. Major corrosion results from reactions electrochemically while general corrosion occurs due to atomic oxidization on same metal surface damaging the entire surface. Generally majority of metals easily oxidize due to loss of electrons to oxygen and form an oxide with metal. Process of reduction and oxidation taking place on different types of metals in contact is known as galvanic corrosion. In electronic equipment water or moisture becomes trapped between two electrical contacts having electrical voltage between them. This process is known as electrolytic corrosion. This results in an unintended electrolytic cell. Harmful corrosion can be prevented in many ways. Some metals naturally resist corrosion by reacting with corrodes in the oxygen in air [2 - 5].

This results in formation of a thin oxide film which blocks the tendency of metal to undergo further reaction. Rust, Galvanic corrosion, Stress cracking corrosion, General corrosion, localized corrosion and Caustic agent corrosion are the six types of corrosions given below:

2. TYPES OF CORROSION

2.1. Rust

Rust is a simple example of corrosion which is considered to be a result of oxidation. It is of importance that not all iron oxides are rust. Rust may be formed when oxygen reacts with iron but at the same time keeping iron and oxygen together is not sufficient to form rust. Fig. (**1**) shows the rust in iron.

2.2. Galvanic Corrosion

Galvanic corrosion is also known as bimetallic corrosion. It is due to an electrochemical process in which two metals are in electrical contact in the presence of an electrolyte where in one metal corrodes. The galvanic corrosion is shown in Fig. (**2**).

Fig. (1). Rust (Courtesy: www.shutterstock.com/).

Fig. (2). Galvanic corrosion (Courtesy: www.azom.com).

2.3. Stress Corrosion Cracking

Enhancement or growth of crack formation in a corrosive environment is known as stress corrosion cracking (SCC) as shown in Fig. (**3**). It may give rise to sudden failing of normal ductile metal alloys if subjected to tensile stress especially at higher temperatures.

CHAPTER 12

Marine Corrosion

H. Manjunatha[1,*], **K. Venkata Ratnam**[1], **S. Janardan**[1], **R. Venkata Nadh**[1], **N. Suresh Kumar**[2], **N.V. Krishna Prasad**[3], **S. Ramesh**[3], **K. Chandra Babu Naidu**[3] and **T. Anil Babu**[3]

[1] *Department of Chemistry, GITAM Deemed to be University, Bangalore - 562163, Karnataka, India*

[2] *Department of Physics, JNTU College of Engineering Anantapur, Anantapuramu-515002, A.P., India*

[3] *Department of Physics, GITAM Deemed to be University, Bangalore-562163, Karnataka, India*

Abstract: Seawater is a hostile environment not only for people but also for metals and alloys. It is often considered that sea water is the most severe environment to which materials can be exposed. Warmer water accelerates the rate of corrosion due to high temperature and particularly aggressive. In this chapter, marine corrosion, its mechanism, factors affecting corrosion and several methods adopted for the prevention of corrosion are described with an emphasis on marine corrosion inhibitors. Organic compounds containing hetero atoms like O, N, S, *etc*., along with double and triple bonds are found to be very effective in preventing marine corrosion of alloys and metals. Most of the corrosion inhibitors are found to show inhibition property by getting adsorbed on to the metal surface through the principle of different adsorption isotherms known. The maximum corrosion inhibition efficiency of organic inhibitors is found to be more than 99%. The use of inorganic compounds and paints as corrosion inhibitors is discussed.

Keywords: Corrosion Inhibitors, Factors Affecting Corrosion, Marine Corrosion, Mechanism of Corrosion, Stainless Steel & Alloys.

1. INTRODUCTION

Corrosion is a 'billion-dollar thief'. Even though it is a natural phenomenon, it results in loss of material, money and life. Metals have a strong crystalline structure, and due to corrosion, they get converted into their salts, making them losing their metallic strength resulting in damage to machinery, structures or equipment in which they are used. Thus, corrosion causes damage to metals and

---

[*] **Corresponding author H. Manjunatha:** Department of Chemistry, GITAM Deemed to be University, Bangalore-562163, Karnataka, India; Tel: +91- 88611 58964; E-mail: hanumanjunath80@gmail.com

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

thereby to society. Corrosion is considered as a most damaging and provocative menace in many countries including India causing approximately a loss of one to five percent in Gross National Product (GNP) of each country as per estimations of NACE (National Association of Corrosion Engineers) [1]. A recent investigation by NACE estimated annual global cost of corrosion to be approximately US $2.5 trillion, which is almost equal to 3.4% of the global GDP [2, 3]. In the US, the total cost of corrosion is more than the US $1.1 trillion [4] annually. The annual corrosion cost of India is more than US $100-billion and that of South Africa; the direct corrosion cost is estimated to be around the US $9.6 billion [2, 3] which may be increased with technology development and usage of metallic substances. This loss of money all over the globe due to corrosion can be reduced up to 35% by applying proper prevention methods. Corrosion also results in loss apart from large economic damage.

For example, an explosion due to corrosion of metallic structure killed over 200 people in Guadalajara, Mexico, in April 1992 [5]. In addition, these fatalities, the series of blasts damaged 1,600 buildings and 1,500 people injured and the total loss due to both direct and indirect effects of corrosion is estimated to be 75 million US dollars [6]. The cost of corrosion is more than the total annual cost of floods, hurricanes, fires, lightning, earthquake and other natural calamities that occur all over the globe annually. Hence, attention is to be given by corrosion, and similarly, the substantial measures may be taken in reducing economic loss and loss of life.

2. WHY DO METALS UNDERGO CORROSION AND WHAT IS THE DRIVING FORCE?

As per Roberge, “A material destructive attack on reacting with the environment is Corrosion” [7]. In general, it is a known fact that most of the metals are unstable in their free state. Extraction of metals from their combined states (a process called Metallurgy) involves the addition of a large amount of heat energy. The metals (Free State) extracted from their ores will be at higher energy state and have a tendency to go into their combined form generally the corrosion products like rust and scale [8, 9]. Thus, they have a natural tendency to revert back to their combined form when exposed to attacking the environment. Thermodynamically, the standard free energy change (ΔG^0) decides the relative rate of corrosion of metals, and in general, higher the ΔG^0 value, greater will be the corroding tendency and *vice versa* [10, 11].

In this chapter, we restrict ourselves to marine corrosion, its mechanism, causes, factors affecting marine corrosion and the latest developments in the various ways of preventing it.

3. MARINE CORROSION AND ITS MECHANISM

Seawater is an aggressive environment for people, metals and alloys. It is considered often that seawater is the most severe environment to which materials can be exposed. Hot waters speed up the corrosion rate due to high temperature and particularly aggressive. This was the major problem towards the end of the Second World War, which led to Pacific campaigns when military equipment got corroded at an unexpected rate in the tropics [12]. Also, corrosion may be severe in colder waters. Various types of destruction can occur to ships, structures and other equipment used in seawater services. Marine Corrosion is a term that describes many problems faced by marine equipment of metal base used in production, processing and transport industries such as pipelines, households, fuel tanks, oil lines, power lines, heat conductors, heat exchangers and several other marine applications. Marine platforms such as ships, offshore structures and steel bridges are at higher risk of corrosion exposed to the seawater environment, particularly after fifteen to twenty years. Cargoes on-board oil tankers and bulk carriers may be highly corrosive. Incidents like Erika in 1999 [13] and Castor in 2000 [14] highlight the threats of corrosion for ships. Fig. (**1**) displays an image of severe corrosion under deck area of an oil tanker [15]. As corrosion may lead to structural material degradation, facilitate fatigue cracks, brittle fracture and unstable failure [16], the integrity of the entire hull structure can be affected considerably.

SUBJECT INDEX

N. Suresh Kumar, P. Banerjee, H. Manjunatha and K. Chandra Babu Naidu (Eds.)

N. SURESH KUMAR

Dr. N. Suresh Kumar is currently working as an assistant professor of Physics at JNTU College of Engineering Anantapur, India. He received his M.Sc. and Ph.D. degrees from Sri Krishnadevaraya University and JNT University, Anantapur, India, respectively. He is an expert in materials physics and nanomaterials divisions. He has published 30 research articles in reputed international journals and 30 book chapters in standard book editions, published by international publishers. He is currently editing a few books.

P. BANERJEE

Dr Prasun Banerjee is currently working as an assistant professor of Physics at GITAM (Deemed to Be) University, Bangalore campus, India. He received his PhD degree from the University of Calcutta, India, and completed 3 years of postdoc experience from Federal University of Goias, Brazil. He completed several project works with the financial support of National as well as international funding agencies. The review of his project works appeared in 50 international research articles and 25 book chapters in standard book editions, published by different international publishers. He is currently editing a few books

H. MANJUNATHA

Dr. H. Manjunatha is currently working as an assistant professor of Chemistry at GITAM (Deemed to Be) University, Bangalore campus, India. He is an expert in materials chemistry and nanomaterials divisions. He published 30 research articles in reputed international journals and 15 book chapters in standard book editions, published by international publishers. He is currently working as an author, reviewer, editor, guest editor of reputed international journals, and publishers.

K. CHANDRA BABU NAIDU

Dr. K. Chandra Babu Naidu is currently working as an assistant professor of Physics at GITAM (Deemed to Be) University, Bangalore campus, India. He is an expert in materials physics and chemistry and nanomaterials divisions. He has published 80 research articles in reputed international journals and 40 book chapters in standard book editions, published by international publishers. He is currently working as an author, reviewer, editorial member, editor, and guest editor of reputed international journals & publishers.