Professor N.P. Gandhi Memorial Lecture 2023

Basics, Innovations and Embracing Challenges Towards Addressing Corrosion in Critical Technologies and Environmental Concerns

IIM-ATM 2023: 77th Annual Technical Meeting of the Indian Institute of Metals

22nd to 24th Nov 2023, KIIT, Bhubaneswar, Odisha

Organised by

THE INDIAN INSTITUTE OF METALS

Professor N. P. Gandhi

On the recommendation of Mahatma Gandhi, Professor N P Gandhi was chosen, as the most eminent personality for establishing technological branches of study at Banaras Hindu University by Pandit Madan Mohan Malaviya, founder BHU.

With his pioneering efforts and meticulous organising abilities, Prof N P Gandhi established a composite Unit of Geology, Mining and Metallurgy at BHU in 1919. In 1923 the Department of Miningand Metallurgy came into existence and the first ever Bachelor's degree courses in Mining and Metallurgy were started.

Prof Gandhi's vision and untiring efforts resulted in production of high quality metallurgical engineers well equipped to meet the Challenges of pre and post independent India. Throughout his career he had striven to establish strong industry linkages and maintain high professionalism. After retirement from BHU in 1942 he continued to take active interest in metallurgical profession and founded the Bombay Metallurgical Society and set up the Metallurgical Testing Laboratory at Deolali, Mumbai.

In 1961, the Indian Institute of Metals instituted the Professor N P Gandhi Memorial Lecture to perpetuate the memory of a great teacher and professional. Since 1980, the BHUMET trust now, TheProf N P Gandhi Memorial & Metallurgy Trust at BHU, is a cosponsor of this lecture series.

Salutations to Professor N.P Gandhi

At the outset I wish to thank the Indian Institute of Metals and the NP Gandhi Memorial Metallurgy Trust for providing me the opportunity to deliver this very distinguished lecture. It is a great honor and privilege to deliver the same to commemorate the pioneering work of Late Prof. N.P. Gandhi. Going through the achievements of this great person is indeed a humbling experience and a great motivation to contribute science and technology for our Country.

Prof. N.P. Gandhi was an illustrious person toping academics at Wilson College in Bombay and Imperial College Science and Technology, London. After serving Copper Works, Japan and Tata Sons Ltd., Tovoy, Lower Burma, on the advice of Mahatma Gandhi, Prof. N.P Gandhi joined Pandit Madan Mohan Malviya, another Institution Builder, in the year 1919 to commence technical education in Banaras Hindu University (BHU) to support Indian Industries. His vision, perseverance and dedication led to the birth of College of Mining, Metallurgy and Geology in 1923 at BHU. The country produced the first-ever bachelor's degree course in Metallurgy from this portal, which blossomed into a great institute for metallurgical education and research in the country.

I shall pay my tributes to Prof. N.P. Gandhi before I commence my lecture entitled "Basics, Innovations and Embracing Challenges Towards Addressing Corrosion in Critical Technologies and Environmental Concerns".

About the Speaker

Prof. VS. Raja is currently Emeritus Fellow in the Department of Metallurgical Engineering and Materials Science, Indian Institute of Technology Bombay, India. He has been Visiting Professor/Researchers at Chalmers University of Technology, Sweden; University of Nevada, Reno, USA; GKSS, Germany; Tohoku University Japan and INSA Lyon France.

Prof. Raja has made pioneering contributions to corrosion education, research and mitigating industrial problems. His research interests span of structure-property-corrosion topics mostly focused on localized corrosion, environmentally assisted cracking of light metals, weld related corrosion, development of novel coating and advanced ultra-critical steam oxidation. He made seminal contributions to the understanding of the mechanisms of stress corrosion cracking of aluminum, magnesium and titanium alloys, steels and stainless steels. His work has unraveled the complex interplay of electrochemistry, surface chemistry of films and the metallurgy of the alloys towards stress corrosion cracking that formed the basis for developing alloys with outstanding SCC resistance.

Prof. Raja supervised over 35 doctoral and 120 masters' students and published over 250 papers in peer reviewed journals and conference proceedings. Lead editor of the book Stress Corrosion Cracking: Theory and Practice and Coauthor of the book " Corrosion Failure Analysis: Basics, Case Studies and Solutions". He is editor of Corrosion Science Journal and editorial advisory member of Corrosion Science, Engineering and Technology and Materials and Corrosion and served as editor of Transactions of Indian Institute of Metals for six long years.

In recognition, Prof. Raja received several national and international awards including, MASCAT award by The Electrochemical Society of India (2003), Excellence in Teaching Award by IIT Bombay (2008 & 2022), Prof. S.P. Sukhatmate Excellence in Teaching Award by IIT Bombay (2016), Meritorious Contribution Award of NACE International India Section (2009); VASVIK award for industrial research (2014), Impactful Research Award by IIT Bombay (2016), ASM-IIM North America Lecture Award (2016), Technical Achievement Award by NACE International USA (2017) and Prof. HH Mathur Award for Excellence in Applied Science, IIT Bombay (2023). Institute Chair Professor ((2010-2014, 2014-2017, 2017-2020 & 2020-2023). He is Fellows of NACE International, USA (2011), Indian Institute of Metals (2014) and The Electrochemical Society of India (2017) and 1st Vice President, International Corrosion Council (2021-24)

Basics, Innovations and Embracing Challenges Towards Addressing Corrosion in Critical Technologies and Environmental Concerns

V.S. RAJA

Department of Metallurgical Engineering and Materials Science
Indian Institute of Technology Bombay
Mumbai 400 076, INDIA
Email: vsraja@iitb.ac.in

Abstract

The subject Corrosion Science and Engineering, by nature, has always been at the forefront of protecting environment even when advanced technologies developed in the Industrial era may not take cognizance of this issue. As all the engineering metals are deemed to suffer corrosion dictated by their thermodynamic, it is imperative to develop these engineering materials to offer reliable and long-lasting service life. Engineering these materials to offer kinetic resistance to corrosion thus forms the basis of materials development. This involves understanding interplay of metallurgy, chemical environments and the operating conditions such as applied stresses. The modern technologies demanding lighter and smart structures, ability for the materials to withstand high temperatures and pressures and being environmentally friendly pose interesting challenges to corrosion researchers to be innovative, understand the basic science of corrosion and also design difficult experiments to simulate the operating conditions. This talk will touch upon a few studies that are of interest to indigenization of robust and environmentally friendly technologies carried out in our laboratory.

Keywords: Al-alloys, environmentally assisted cracking, protective coatings, AUSC oxidation

1. Introduction

Metallic materials are widely employed as structural materials to build infrastructure, industrial plants and transportation systems and as well as in manufacturing devices to meet various needs of human kind. A closer look at the metallic elements employed for structural applications and the majority of those used to manufacture devices are dictated by thermodynamics that they suffer corrosion in chemical environments of various kinds. The threat to corrosion induced failure of structures increases with the need to apply them in more stringent conditions such as deep-sea exploration of resources and light weighting structures and Advanced Ultra Super Critical Power Plants (AUSC). These technologies are vital as the resources in earth crest deplete and the global warming due to carbon dioxide emission possess a greater threat to the human kind. In addition, advanced manufacturing technologies such as additive manufacturing are expected to alter the corrosion behavior of metallic materials.

As suggested earlier, the engineering alloys have the inherent thermodynamic tendency to corrode which cannot be changed. The successful application of alloys to manufacture reliable, safe and long-lasting structures, therefore, hinges on importing kinetic resistance to the corrosion of these alloys. This essentially means understanding the underlying corrosion mechanisms. These mechanisms vary significantly and can become complex as the alloys are made into structures and devices to perform different function (for examples corrosion related to pipelines, pressure vessels, welded and unwelded structures, electronic devices differ significantly) Corrosion in aqueous environments is primarily governed by electrochemical phenomena. These phenomena, is greatly influenced by the metallurgy of the alloy at microscopic and atomic level while the role of environment in altering electrochemical phenomena needs no emphasis, the mechanical aspect of structure in change the corrosion mechanism is very important. Thus, a larger goal in developing alloys having higher corrosion resistance must involve understanding the inter play of electrochemistry, metallurgy and mechanical. The core objective of corrosion research in our group has been to address these aspects for alloys ranging from stainless steels, aluminum alloy, titanium alloys, nickel base alloys, iron based intermetallic and maraging steels towards this goal. As protective coatings are the most widely employed technology to mitigate corrosion, especially where the alloys meet the mechanical requirements but fail to offer corrosion resistance (steels for atmospheric applications and nickel base alloys for high temperature applications), research towards novel and environmentally friendly coatings was directed. Notably, our research emphasis has been towards materials and technologies that are developed in our country and yet focus on understanding the corrosion mechanisms. In that direction, we have developed indigenous facilities to study the oxidation performance of nickel base alloys and stainless steels in steam at Advanced Ultra Super Critical (AUSC) conditions (710^{o}C and 32 MPa), a step towards realizing such thermal power plants. In this lecture I shall present briefly some of our work related to (1) Development of high strength and high environmentally assisted cracking (EAC) resistant aluminum alloy, (2) Development of novel and eco-friendly coating and (3) some challenges in establishing test facilities to study oxidation behavior of metallic materials for AUSC applications.

2. Development of high strength and high environmentally assisted cracking resistant Al-alloys:

2.1 Role of grains boundary and matrix precipitates.

This work started almost two decades back when Dr. A.K. Mukhopadhyay was indigenizing 7010 Al-alloy. The primary aim was to develop heat treatment other than the conventional over aging (OA) and industrially unsuitable retrograde raging treatment (RRA) to increase strength and resistance to EAC. This was done by aging below G.P. solvus line to promote homogenous nucleation and then subject the alloy to peak and over aging (1). As it turned out, the peak-aged alloy tested in 3.5 wt.% NaCl at a strain rate of $1x10^{-6}$ having $\sigma_{uts} =$ 575 MPa and ε = 12% in air suffered intergranular showing with $\sigma_{uts} =$ 575 MPa and ε = 3%. Thus, a remarkable 66% reduction in ductility for the alloy in the environment was noticed. On the contrary, the overaged alloy showed $\sigma_{uts} =$ 560 MPa and ε = 13% in air and in the environment, it showed $\sigma_{uts} =$ 560 MPa and ε = 12% almost retaining its ductility shown in the air. Notably, the over aged alloy lost about 15% of its strength (Figure 1 a-b). A detailed investigation lead to our belief that, the intergranular cracking was mainly associated with a relatively more anodic character of the grain boundary precipitates (GBPs) namely $MgZn_2$(Cu). Upon over aging, these GBPs turned relatively noble due to enrichment of Cu (Figure 1c). Through detailed analysis, we proposed the preferential dissolution of the GBPs is the main reason, which needs to be suppressed in order to promote EAC resistance to the alloy.

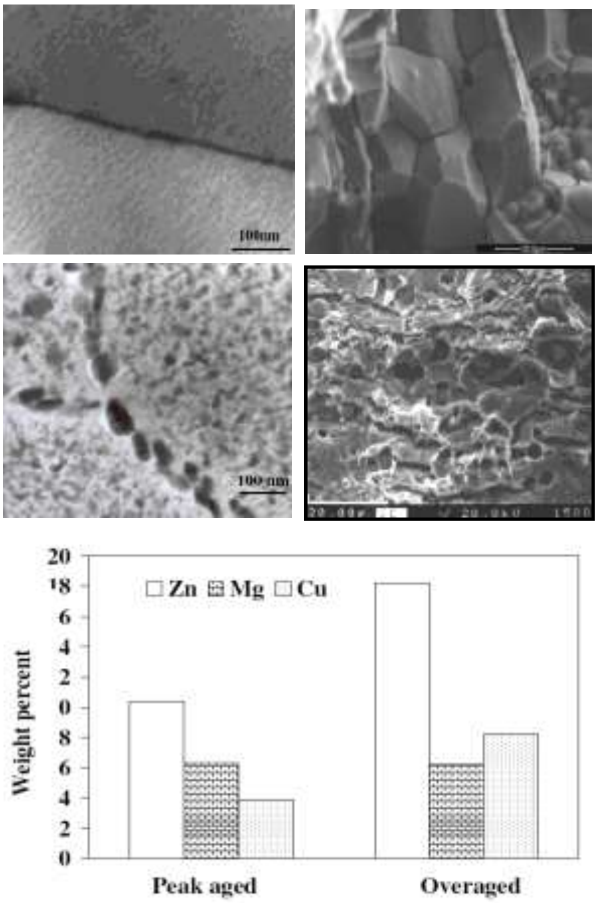

Figure 1 Top figures for peak aged 7010 Al-alloy. Left: TEM image of the alloy and Right depicts intergranular fracture occurred in SSR tested specimen. Middle figure for the overaged alloy. Left: TEM image of the alloy and Right depicts ductile transgranular fracture occurred in SSR tested specimen. The plot at the bottom is energy dispersive x-ray analysis data of grain boundary precipitates. Note a significant increase in the GBPs of the over aged alloy (ref.1)

This happens when the copper content of the GBPs is increased to make the latter noble. This mechanism of the active grain boundary precipitates causing EAC was first of its kind as hitherto EAC susceptibility of the alloys were considered to be due to the coherent precipitates in the overaged alloy has been suggested promote plan slip. On over aging, the precipitates turned incoherent which is expected promote cross-slip and hence retain the ductility of the alloy even in corrosive environments. This aspect will be discussed in details later.

2.2 Role of recrystallization:

The fact the GBPs in the peaked alloy is predominantly responsible for the EAC susceptibility of the alloy, lead to the conclusion that suppressing recrystallization can further explore the EAC resistance of the alloy. The base alloy AA 7010 has Zr which forms Al_3Zr dispersoids. These dispersoids are expected to suppress recrystallization but are found be less effective. A.K. Mukhopadhyay increased added Sc to this alloy that formed $Al_3Sc_xZ_{1-x}$ precipitates are more effective in inhibiting recrystallization. Unsurprisingly the Sc added alloy showed remarkable EAC resistance even in the peak aged condition (Figure 2) (2). Thus, the Sc added alloy is air showed σ_{uts} = 560 MPa and ε = 13% and in 3.5 wt% NaCl tested using slow strain rate test at $1x10^{-6}$ strain rate showed σ_{uts} = 560 MPa and ε = 12%, which is remarkable as the alloy has high strength as well as high EAC resistance. However, considering Sc is a strategic element, this is not a viable technology to produce Al-alloys having high strength as well as high EAC resistance.

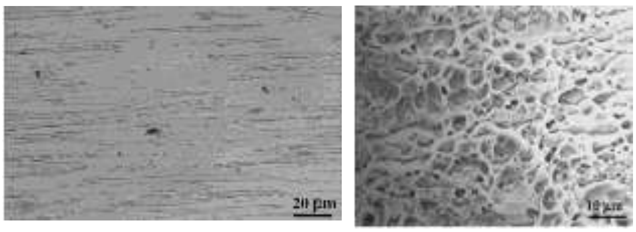

Figure 2. Left optical image of the Sc added 7010 Al-alloy and the right the fracture features of SSR tested alloy showing ductile features (ref.2)

2.3 Designing Alloys with noble GBPs and fine matrix precipitates.

The foregoing work has shown that so long as the GBPs are noble, the alloy will resist EAC. Therefore, it is possible to have fine (coherent) precipitates within the grains, the alloy is expected to resist EAC so long as the GBPS are noble in character. This way, it is possible to achieve Al-alloys with high strength as well as high EAC resistance. It is desirable that such a treatment can be employable in industries. The PhD research scholar Ajay Krishnan examined various possibility and came out with a modified T6I6 treatment, to shorten the aging time significantly and termed it as modified aging (3-5). The low-temperature aging treatment facilitated large five precipitates due to high under cooling as well a significant reduction in the solubility of Cu. Figure 3 compares the types of precipitates found in the peak aged, over aged and T6I6 aging conditions for 7010 Al-alloy (3). Higher population fine precipitates rendered high strength to the alloy and significantly high Cu content of GBPs (to the tune of about 6 wt.%) further resisted IGC. A twin objective of high strength and high EAC resistance could be achieved not only for 7010 Al-alloy but also for 7050 Al-alloy.

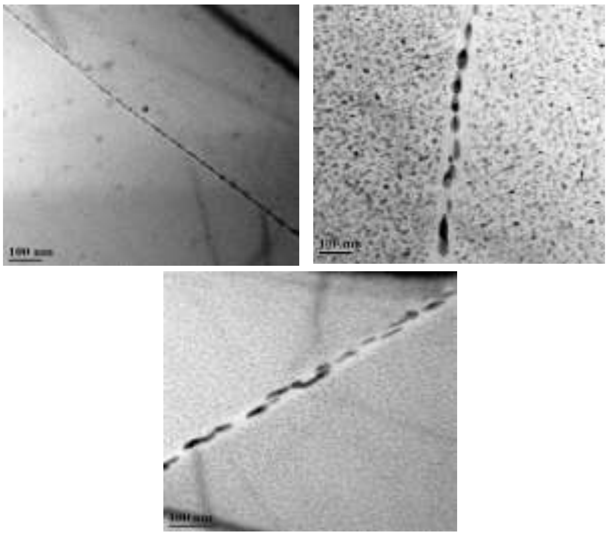

Figure 3 Comparison of TEM images of (a) peak aged, (b) overaged and (c) T6I6 aged 7010 Al-alloy (ref.3)

Figure 4 shows a typical slow strain rate curve for 7050 Al-alloy tested in 3.5 wt.% NaCl at the 10^{-7} strain rate (4). As can be seen that MA alloy showed a remarkable 100 MPa higher tensile than the conventional over aged alloy with even a marginal increase in the ductility of the alloy. Thus, the twin objectives of achieving high strength as well as high EAC resistance has been achieved. This work has been patented (5,6). While the above results are encouraging, fracture mechanics studies on notched specimens and hydrogen charging on smooth cylindrical specimens show that modified aged and over aged 7010 Al-alloy suggest that at high hydrogen concentrations, these alloy can be made susceptible to EAC even in these improved metallurgical conditions (7) Therefore, there is a need to understand more in depth the governing factors controlling EAC. This aspect is

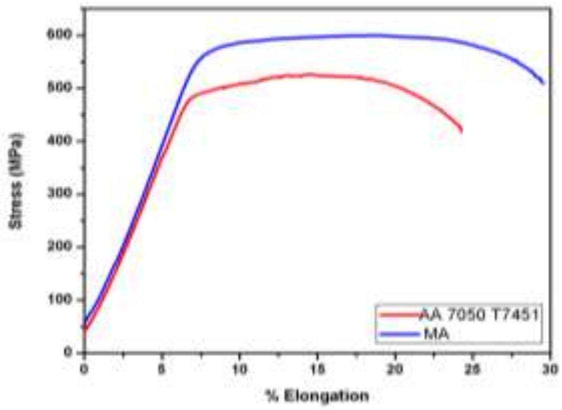

Figure 4 Slow strain rate test plots of AA 7050 obtained in 3.5 wt.% NaCl obtained at $1x10^{-7}$ strain rate (ref.4)

2.4 Deformation electrochemistry metallurgy in EAC of 7050 Al-alloy.

Environmentally assisted cracking susceptibility is evaluated using a slow strain rate test (SSRT). The loss in elongation for a specimen subjected to SSRT in a given environment in relation to the elongation shown by the alloy in air is considered as an indication of the extent of EAC susceptibility an alloy in a given environment. Rahul Kumar Agrawal, in his doctoral work has shown that work hardening is a better reflection of EAC susceptibility of 7004 Al-alloy than elongation (8). Using the 7004 Al-alloy he shown that even though the alloy ductility does not get affected due to the environment (3.5 wt.% NaCl), its work hardening parameter significantly changes due to the environment.

Later, he followed up this aspect by examining Geometric phase analysis, to determine the atomic strain in the alloy with and without exposure to environment at a given strain (9). A detailed study in this direction was further undertaken to understand Deformation-Electrochemistry-Metallurgy in EAC of 7050 Al-alloy by Shweta Shukla in her doctoral work. A brief account of this work is provided here. A more detailed account of her work can be found in our publications (10-12)

Several types of aging (T6, T73, T6I6, MA, RRA) are carried out to towards raising the mechanical behavior of Al-alloys. In each of these cases phases differing in nature and volume fraction are generated. The question is, can we understand how these phases influence electrochemical and deformation behavior that ultimately decide the EAC tendency of Al-alloys. To address this question Shweta tailored heat treatments to generate variation in phases (quantitative or qualitative as it was not possible just to produce one kind of phases) (10) (Table). In all these cases the noble character of the GBPs precipitates was maintained to suppress the intergranular cracking behavior of the alloy.

Table 1 Phases formed in 7050 Al-alloy

Heat treatment	Matrix Precipitates size	Phases present
OA	13 ± 4 nm	η’ and η
MA5	7.6 ± 2 nm	GP I, GPII, η’ and η
MA3	5.4 ± 1 nm	GPII and η’

These had very interesting outcome which can be summarized as follows:

(1) The metastable phases GP II zone and GPI zone showed higher hydrogen kinetics ($2H_2O_{(l)} + 2e^- \rightarrow H_{2\,(g)} + 2OH^-_{(aq)}$ & $2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)}$) and lower oxygen reduction kinetics ($O_{2\,(g)} + 2H_2O_{(l)} + 4e^- \rightarrow 4OH^-_{(aq)}$) in relation to the over aged alloy that contain η’ ($MgZn_2$) matrix precipitates and η ($MgZn_2$) GBPs (Figure 5). It is known that hydrogen evolution reaction is detrimental and oxygen reduction reaction is beneficial towards EAC resistance of the alloy. Therefore, the above observations are rather surprising as alloys with GPII zones and GPI zone are detrimental than η’ and η from the electrochemical point of view and yet the alloy with these precipitates showed higher uniform elongation (less localization) and better strength and EAC resistance than OA alloy having η’ as matrix precipitates.

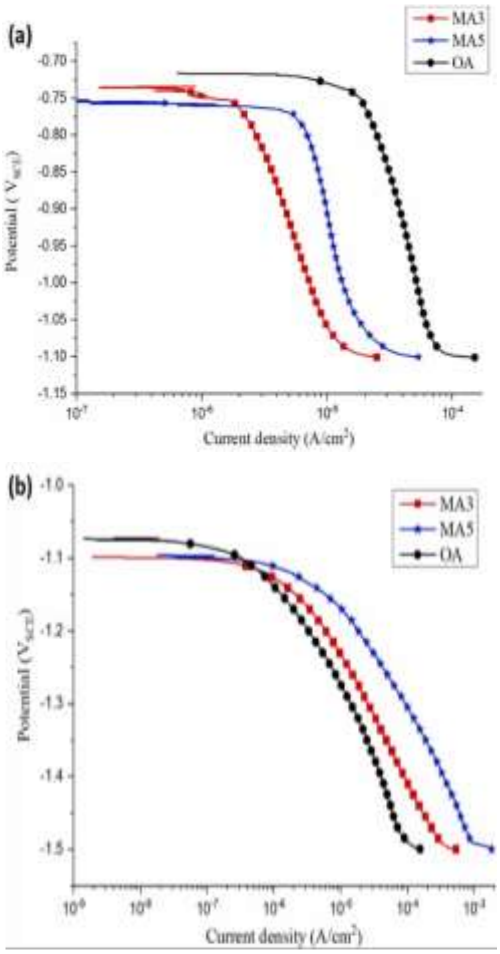

Figure 5 Polarisation curves of the OA, MA5 and MA3 in (a) freely exposed (b) deaerated 3.5 wt% NaCl environment (ref.10)

(2) The work hardening Θ_{max} and dynamic recovery rate $^{d\theta}/_{d\sigma}$, showed that hydrogen charging promotes cross-slip in the alloy with coherent precipitates, while it promotes planar ship in the alloy having semi coherent precipitates (Figure 6). The work also brings out the role of hydrogen and the nature of precipitates in generating dislocation and its effects on recovery rate. The precipitate electrochemistry-dislocation interaction is presented schematically in Figure 7.

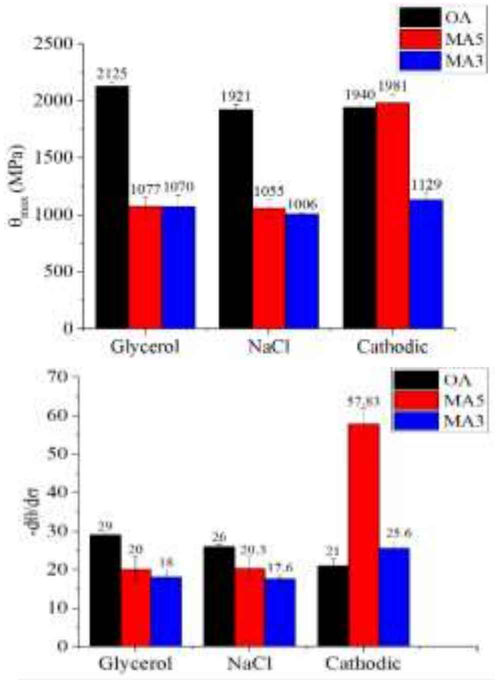

Figure 6 Work hardening parameter and dynamic recovery rate for 7050 Al-alloy under various testing conditions (ref.10)

(3) The main outcome of the work is that there is still a large scope in improving the EAC resistance of copper containing 7xxx Al-alloy. Computational materials science can help to arrive at precipitates chemistry that will have lower hydrogen evolution kinetics and higher oxygen reduction kinetics without compromising on the coherent character of precipitates. Such modification in precipitates chemistry to suppress hydrogen chemistry is expected to show high strength along with high EAC resistance.

3. Development of Innovative coatings for Corrosion Protection

Protective coatings are a one of the majorly employed technologies to protect metals against corrosion. Among the coatings, paints/organic coatings are the most widely employed due to its versatility. within the metallic coatings zinc applied through hot dip technique stands the most. The application of paints is fraught with pollution due to emission of volatile organic compounds (VOC), due to extensive use of solvents, mostly organic in nature. Typically, these paints release 28.8 gm of volatile compounds in air per litre of paint employed.

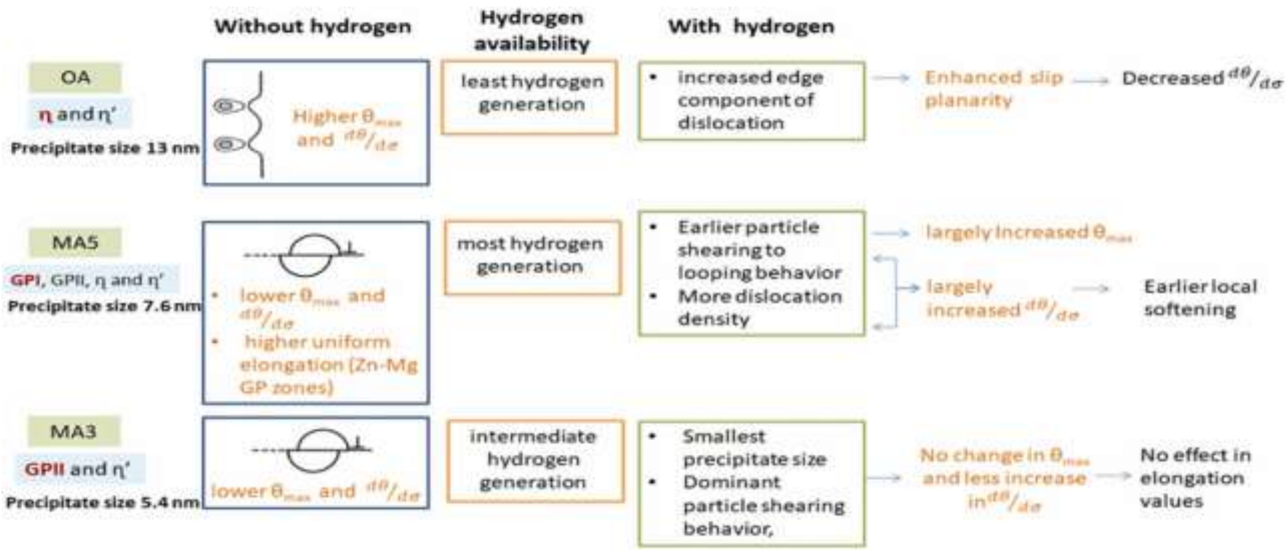

Figure 7 The finding of the work can be summarized schematically as above (ref.10)

As far as the zinc coatings are concerned with the raising cost of zinc, it is becoming very expensive and there is a need to reduce zinc coating thickness to enhance the service life of the zinc coating. Innovative means were applied to address these problems.

3.1. Development of thermally sprayable polyethylene coatings

This is the doctoral work of S.K. Singh, Naval Materials Research Laboratory and master's work of Rashmi David. Low-density polyethylene (LDPE) is quite less expensive. But it lacks adhesion to metals when applied as coating, as there are no polar groups in polyethylene. This was addressed by grafting the low-density polymer with maleic acid using a versatile technique called reactive extrusion. More details can be found in the publications (13-16). Extrusion gave the LDPE a polar character (Figure 8). The grafted LDPE was cryoground into fine powders and the coating was applied through flame spray technique. Optimization of the parameters are required to ensure that the coating does not disintegrate due to exposure to flame. The coating so obtained showed significantly higher adhesive strength from 5.4 MPa to 8.8 MPa due to maleic acid grafting. Typical Bode plot obtained on the coated panel exposed to simulated sea water is shown in Figure 9. As can be seen the coating showed an excellent impedance, meaning high resistance to corrosion even after long exposure to sea water.

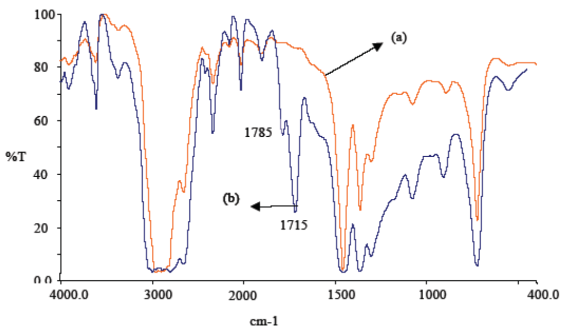

Figure 8 FTIR spectrum of (a) LDPE and (b) LDPE-g-MAc, 8% maleic acid (ref.14)

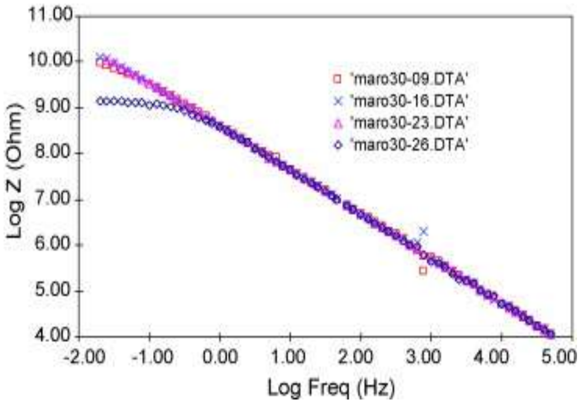

Figure 9 Bode plots of LDPE-g-MAc+ 0% red iron oxide after (□) 9 days; (✕) 16 days; (△) 23 days; (◊) 26 days). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article (ref.14)

3.2 Development of high-performance hot dip galvanized coatings.

S.T. Vagge, for his doctoral work, carried out an interesting study on very conventionally used hot dip coatings. The objectives of the work are (a) to improve the formability of the coating (b) increase its corrosion protection capability. The main approach to address the problems is to refine the grain size of the zinc coatings strontium being an effect element to refine Al-Si coatings, it was employed in that study. He published series of papers exploring the influence of Sr on modification the grains and its effect on adhesion, formability and corrosion resistance (17-20). He also utilized simple polarization technique to determine the coating delamination that might occur during sheet metal forming. The Sr addition has been found to show significant improvement in the corrosion resistance, adhesion strength and delamination resistance of hot dip zinc coating. Subsequently, with the help of coating simulator and Mahesh Walunj, we were finally able to demonstrate the significant beneficial effect of Sr addition on the corrosion resistance of Sr added coatings. For a coating thickness of ~10 μm addition of 0.02 wt.% Sr gave rise to a change in grain size from 593 μm to 145 μm (Figure 10) and salt spray life from h to h, thus demonstrating a form-fold improvement in corrosion performance (Figure 11) through adding trace amount of strontium.

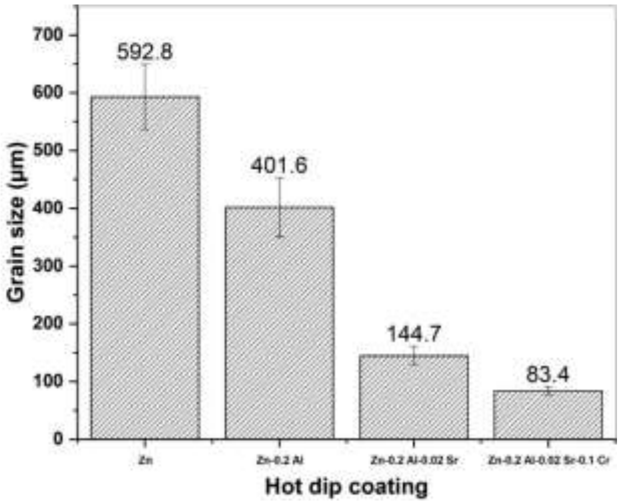

Figure 10 Comparison of grain size of various zinc coatings

Figure 11 Comparison salt fog exposed coated panel (a) plain zinc coating and (b) Zn-0.02Sr Coating.

4. Indigenous development of high temperature and high-pressure test loop and study of oxidation performance of Alloys for Advanced Ultra Super Critical Power Plants- A Challenging Task.

In the era of global warming increase in thermal efficiency of coal fired boilers to reduce carbon dioxide emission needs no emphasis. Advanced Ultra Super Critical (AUSC) power plants projected to operate around 710°C and 32 MPa is expected to offer thermal efficiency close to 50%. The stability of materials against corrosion in waterside at this temperature is critical for reliable and safe operation of power plants.

We have taken upon ourselves to establish a facility in the country to study oxidation behavior of potential alloys in AUSC environment. Figure 12 shows typical photos of various units. The flow diagram outlines the various associated units. Several alloys namely IN617, 740H, 304HCu and Sanicro 25 are under investigation. Here I bring out some salient results related to IN617, an alloy proposed to be employed in AUSC power plants.

In a recently published review by Ghule et al. (21), it has been brought out that only limited studies have been carried out on the oxidation behavior of IN617 alloy. It is hard to make definite conclusions on the behavior of the because of the fact that the water chemistry is either not specified or at too high oxygen levels. Therefore, a study was undertaken to simulate the water chemistry. The detailed work can be found in ref. 22. Typical kinetic curves of the alloy obtained at 710°C and 650°C with 32 MPa are shown in Figure 13 (22). Within the test duration of 600 h, the alloy showed less significant weight gain with near parabolic kinetics detailed mechanism of oxidation has been well brought out in the publication. The formed oxides were studied using Raman spectroscopy and transmission electron microscope.

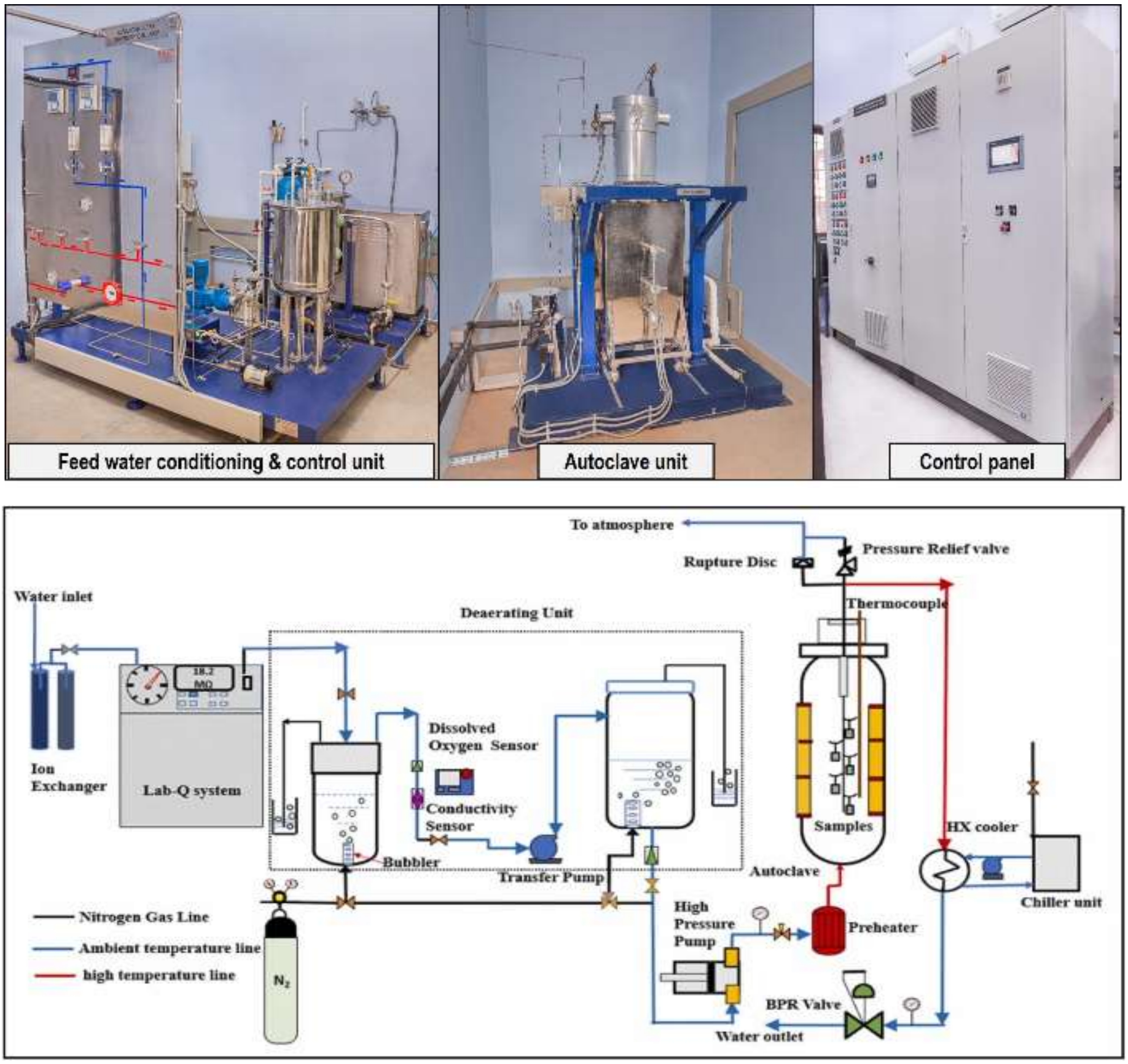

Figure 12 (a) Photos of the three major units of the AUSC test loop employed for the steam oxidation studies and (b) Schematic of the Advanced Ultra-Supercritical steam oxidation test facility (ref.22)

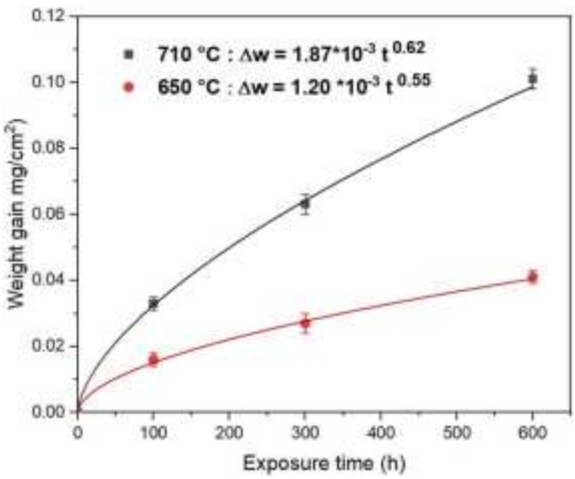

Figure 13 Oxidation kinetics of the alloy 617 in AUSC steam at 650 °C and 710 °C temperatures (ref.22)

The study revealed the oxidized alloy to have bilayer oxides, with the outer oxide being spinel of type MCr_2O_4 and the inner oxide being Cr_2O_3 (Figure 14). A notable outcome of the work is that no significant chromium volatilization has been observed in this alloy.

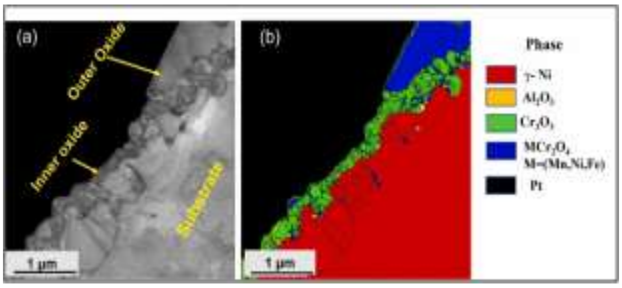

Figure 14 PED analysis and the resulting **(a)** Index map and **(b)** phase composition map of oxide scales formed on alloy 617 after 600 h in AUSC steam at 710℃.

5. Concluding Remarks

Corrosion is an important rate determining step in controlling the service life of engineering components. With the growing concerns of depletion of resources and deteriorating environment the emphasis on corrosion mitigation has gathered a great momentum. The modern technologies make the corrosion mitigation more complex. The way forward to address the corrosion issues is to understand the corrosion mechanisms followed by innovation to develop new materials and protective measures and take up challenging research as demanded by the advanced technologies. This talk and the paper highlight these aspects through the work carried out in our laboratory.

Acknowledgements: Received generous funding from DST, SERB, DRDO, BRNS, AICTE and the outcome of the work has been due to Doctoral and Masters' students.

References

1. M. Bobby Kannan, V.S. Raja, R. Raman and A.K. Mukhopadhyay, Influence of multi-step aging on the stress corrosion cracking behavior of 7010 Al-alloy, Corrosion, 59, (2003) pp881-889

2. M. Bobby Kannan, V.S. Raja, A.K. Mukhopadhyay and P. Schmuki, Environmental assisted cracking behavior of peak aged 7010 aluminum alloy containing scandium-metall. and mater. Trans.36A, (2005), pp. 3257-326

3. M. Ajay Krishnan and V.S. Raja, Development of a high strength AA7010 aluminium alloy resistant to environmentally assisted cracking, Corros. Sci., 109 (2016) pp.94-100

4. M. Ajay Krishnan, V.S. Raja, Shweta Shukla and S.M Vaidya, Mitigating intergranular stress corrosion cracking in age hardenable Al-Zn-Mg-Cu alloys, Metallurgical and Materials Transactions-A, Vol. 49A, (2018) pp.2487-2498

5. Ajay Krishnan, V.S Raja and S. M. Vaidya, Four-step thermal aging method for improving environmentally assisted cracking resistance of 7xxx series aluminium alloys, Indian Patent Application No 201621026704

6. Ajay Krishnan, V.S Raja and S. M. Vaidya, Four-step thermal aging method for improving environmentally assisted cracking resistance of 7xxx series aluminium alloys, International Application under the PCT No PCT/IN2016/000280

7. M. Ajay Krishnan, V.S. Raja, Role of temper conditions on the hydrogen embrittlement behavior of AA 7010, Corrosion Science, 152 (2019) pp 211-217

8. Rahul K. Agarwal and V.S. Raja, Effect of environment on the work hardening behavior of AA7004, Metallurgical and Materials Transactions, 52A, (2021) pp 1465-1476

9. Rahul Kumar Agrawal and V. S. Raja, Effect of 3.5 wt.% NaCl and cathodic charging on the atomic strain distribution of a plastically deformed AA 7004, Corrosion, *78*, (2022) pp. 404–414

10. Shweta Shukla, Balila Nagamani Jaya, and V.S. Raja, Understanding the role of matrix precipitates on the environmentally assisted cracking behavior of AA 7050 alloy, Corros. Sci., 201, (2022) 110281

11. Shweta Shukla, Balila Nagamani Jaya, and V.S. Raja, Role of metastable-ɳ' precipitates and GPII zone on the environmentally assisted cracking of AA 7050 alloy, Metallurgical and Materials Transactions A (under revision)

12. Shweta Shukla, Balila Nagamani Jaya, and V.S. Raja, Micromechanisms of dislocation-precipitate interactions in AA7050 alloy in the presence of hydrogen, J. Alloys and Compounds, 947, (2023), 169596

13. S.K. Singh, S.P. Tambe, A.B. Samui, V.S. Raja and Dhirendra Kumar, Maleic acid grafted low density polyethylene for thermally sprayable anticorrosive coatings, Progress in Organic Coatings 55 (2006), pp. 20-26

14. S.K. Singh, S.P. Tambe, V.S. Raja and Dhirendra Kumar, Thermally sprayable polyethylene coatings for marine environment, Progress in Organic Coatings 60 (2007) pp186-193

15. S.K. Singh, S.P. Tambe, G. Gunasekaran, V.S. Raja and Dhirendra Kumar, Electrochemical impedance study of thermally sprayable polyethylene coatings, Corros. Sci., 51 (2009) pp. 595-601

16. Rashmi David, S.P. Tambe, S.K. Singh, V.S. Raja, Dhirendra Kumar, Thermally sprayable grafted LDPE/nanoclay composite coating for corrosion protection, Surface Coatings Technology, 205, (2011), pp 5470-5477

17. V. S. Raja, C. K. Panday , V. S. Saji and S.T. Vagge and K. Narashiman, An electrochemical study on deformed galvanneal steel sheets, Surface and Coatings Technology, 201(2006) pp. 2296-2302

18. S.T. Vagge, V.S. Raja and R. Ganesh Narayanan, Effect of deformation on the electrochemical behavior of hot-dip galvanized steel sheets, Applied Surface Science, 253 (2007), pp 8415-8421

19. S.T. Vagge and V.S. Raja, Influence of strontium on electrochemical corrosion behavior of hot-dip galvanized coating, Surface Coating Technology, 203 (2009) pp. 3092-3098

20. V.S. Raja and S.T. Vagge, An improved protective coating composition for hot dip galvanization of steel, Indian Patent No 256103 (247/MUM/2008)

21. Bhagwat Ghule, C. Sundaresan, D. Vijayshankar D and V.S. Raja**,** Oxidation behaviour of Ni-base superalloys in supercritical water – A Review, J. Indian Inst. Sci., 102, 2022, pp. 351–389

22. Bhagwat Ghule, C. Sundaresan, S. Ningshen and V.S. Raja, Oxidation behaviour of Ni-base superalloy 617 in simulated advanced ultra super critical (AUSC) steam, Corros. Sci., 224, (2023) 111503