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POSITION PAPER

Materials and Corrosion

Corrosion challenges towards a sustainable society

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Abstract

A global transition towards more sustainable, affordable and reliable energy systems is being stimulated by the Paris Agreement and the United Nation's 2030 Agenda for Sustainable Development. This poses a challenge for the corrosion industry, as building climate-resilient energy systems and infrastructures brings with it a long-term direction, so as a result the long-term behaviour of structural materials (mainly metals and alloys) becomes a major prospect. With this in mind "Corrosion Challenges Towards a Sustainable Society" presents a series of cases showing the importance of corrosion protection of metals and alloys in the development of energy production to further understand the science of corrosion, and bring the need for research and the consequences of corrosion into public and political focus. This includes emphasis on the limitation of greenhouse gas emissions, on the lifetime of infrastructures, implants, cultural heritage artefacts, and a variety of other topics.

KEYWORDS
corrosion, corrosion costs, corrosion protection, preventive strategies

1 | FOREWORD

Corrosion has been the subject of scientific study for more than 150 years and it remains as relevant today as it was then. In fact, the 2001 U.S. Federal Highway Administration cost of corrosion study, *Corrosion Costs and Preventive Strategies in the United States*, determined the annual direct cost of corrosion to be a staggering US$ 276 billion—or 3.1% of the gross domestic product. Other studies in China, Japan, the United Kingdom, and Venezuela showed similar or even more costly results, leading to an estimated worldwide direct cost exceeding US$ 1.8 trillion. Corrosion is so prevalent and takes so many forms that its occurrence and associated costs will never be completely eliminated. However, the majority of studies estimate that 25%–30% of annual corrosion costs could be saved if optimum corrosion management practices were employed.

Like other natural hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damage to everything from pipelines, bridges, and public buildings to vehicles, water and wastewater systems, hydrogen infrastructure, smart home and city appliances, electronics, batteries, sensors, and even nanotechnologies. Unlike weather-related disasters though, there are time-proven methods to prevent and control corrosion that can reduce or eliminate its impact on public safety, the economy, and the environment. However, investment in new technologies for biodegradability and programmable corrosion are still needed.

Changing climatic conditions as well as other environmental factors are major influences and it is imperative that corrosion professionals understand the effects of these. These factors include the decarbonisation of many industrial sectors; contamination of atmosphere; soil resistivity; humidity and the effect of exposure to salt water on various types of materials; the type of product to be processed, handled or transported; prediction of lifetime of the structure or component; proximity to corrosion-causing phenomena such as stray current from rail systems; appropriate mitigation methods; and other considerations before determining the specific corrosion problem and specifying an effective solution.

For future generations, obtaining a thorough understanding of the science and prevention of corrosion is vital, and to do this innovation of education and training using latest IT approaches such as augmented and virtual reality or artificial intelligence (AI) is crucial. While for corrosion engineers, knowledge sharing between individuals and societies throughout the world is a critical component of corrosion prevention. For example, a serious corrosion problem in one location, such as failure of a ship hull or underground gas pipeline, may have already been solved by colleagues in another part of the world. Digitalisation of industry, collection of data, data mining, sharing and security can improve prevention against failures, and accidents caused by corrosion attack. This urgent need for global collaboration has led to the establishment of international associations for exchange of knowledge, raising public awareness of corrosion, identifying best practices, providing expertise, and establishing global standards.

The EFC, together with the Australasian Corrosion Association, the Chinese Society for Corrosion and Protection, the Association for Materials Protection and Performance, and the World Corrosion Organisation (WCO) have a major role in ensuring that governments, industry, academia, and the general public understand that following appropriate strategies and obtaining sufficient resources for corrosion programmes is not only the best engineering practice, but also a smart investment preventing highly expensive industrial failures and accidents. It also means that other safety hazards, linked indirectly with health, quality of environment and ambitious climatic plans can also be minimised. The payoff includes increased public safety, reliable performance, maximised asset life, environmental protection, and more cost-effective operations on the long term.

Despite the many organisations, strategies and preventative solutions, challenges in corrosion science and engineering remain. The EFC and the WCO though have an eye on the future with a raft of innovative ideas that embrace new technologies from some of the brightest minds in the global industry of corrosion prevention.

2 | CORROSION IN THE SOLAR ENERGY SECTOR[1]

"Renewables grow rapidly in all scenarios, with solar energy at the centre of this new constellation of electricity generation technologies."[1] Solar energy can generate heat and electricity, giving rise to two technologies: solar thermal power that collects and transforms sunlight into heat and then often into electricity; and photovoltaic (PV) technology which converts sunlight directly into electricity. Not only the efficiency of the installations (and hence the electricity price) but also the reliability can be compromised by materials failures due to environmentally assisted degradation. Both technologies use electronic devices, for which corrosion is an important issue common to other sectors, but other elements of solar energy systems need to be considered.

Atmospheric corrosion of the reflective surfaces used to concentrate thermal energy is a specific concern for solar thermal systems. However, a more important issue is related to the high operating temperature at which metallic materials are exposed to in the primary heat transfer media (gas, liquid metals, molten salts, [supercritical] water, or organic fluids). This problem concerns all high temperature conversion systems and the knowledge developed in other sectors could be transferred to solar thermal. For instance, the use of liquid metals (lead, sodium), largely developed in the nuclear energy industry, may be easily adapted to solar thermal technologies. Collaborative strategies and technologies could tackle corrosion issues in high temperatures environments, including the development of corrosion resistant alloys (CRAs), for instance, in molten salts.

The most common corrosion issue in PVs is atmospheric corrosion of the metallic components of the mounting system (aluminium, steels, stainless steel, etc.). The effects of climate, atmospheric pollution, sea/salt spray (Figure 1), and so forth cannot be neglected because they may lead to significant degradation even after only 1 year of exposure.[2] Galvanic corrosion is a specific problem

FIGURE 1 Salt deposit on solar panels in coastal climate (photo: Daniel Lincot). [Color figure can be viewed at wileyonlinelibrary.com]

[1]Authors of the chapter: Polina Volovitch, Steve Paterson, Damien Féron

because most of the racking system components and solar module frames are made of aluminium alloy but some bolts and nuts are stainless steel, bronze, or brass.

PV modules are often considered to be the most reliable elements of the system thanks to the glass protection and encapsulation. Nevertheless, corrosion remains one of the major reasons for failure for busbars (usually made from copper, silver, or aluminium), metallic contacts (molybdenum, aluminium, copper), solders and sometimes silicon. In addition to atmospheric corrosion causing failure of encapsulation, backsheet or frontsheet protection, more specific corrosion mechanisms can be activated by the degradation of polymeric packaging, for example, formation of acetic acid by EVA discoloration, or by high electric field effects. Complexity of corrosion mechanisms in solar cells also results from the multilateral structure and the possible formation of a confined zone in case of delamination. Not only metallic materials but also semiconductors, for example, transparent conductive oxides (intrinsic or doped zinc oxides, tin, or indium oxides) are prone to environmentally assisted degradation. Understanding of failure mechanisms and the key parameters affecting degradation kinetics helps to focus on the most important factors to produce long-term stable modules and systems (Figure 2). This will help also to enable failure specific tests to be developed as well as numeric models to overcome the long-term field exposure for validation of new technologies. Despite the progress achieved in the last decades, many questions, such as the linearity and the precise impact of climate, pollutants, combined effect of voltage and humidity, and so forth have not been properly answered yet and need further research and development.

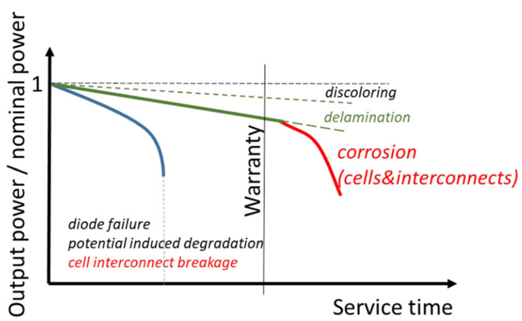

FIGURE 2 Degradation modes affecting operating power loss of c-Si PV modules.[3] [Color figure can be viewed at wileyonlinelibrary.com]

3 | CORROSION IN THE GEOTHERMAL ENERGY SECTOR[2]

Geothermal energy is a constant source of energy compared to solar and wind. It provides power generation, heating or cooling, from various resources: aquifer systems, high temperature hydrothermal and hot rock resources. Geothermal power plants are operating in 29 countries with a total installed power generation capacity of 15.4 GW at the year-end 2019. With ongoing development an additional 50 countries could see the addition of geothermal power generation to their energy mix. Globally, geothermal power generation capacity could reach 28.0 GW in the next 15–20 years.[4]

Each geothermal source is unique in terms of temperature, chemistry of the geothermal fluids, depth and location. One of the difficulties is the variety of corrosiveness of geothermal fluids. The corrosive potential of geothermal energy sources is very varied depending on the chemicals present within the geothermal fluid and steam, and dictates the materials to be selected for constructing the well, turbines, and other equipment. A large range of metals and alloys are used for the wide diversity of geothermal fluids. Carbon steels, often combined with injection of corrosion inhibiting chemicals, are the most common material used, but can still be very susceptible to corrosion. Depending on the specific characteristic of the geothermal fluid environment, corrosion rates may be acceptable for long term use. However, in highly corrosive geothermal fluids, excessive corrosion damage can occur in carbon steels, and alternative materials are normally used. Low alloys steels and stainless steels (e.g., martensitic or austenitic) provide some immunity depending on the conditions, but duplex and superaustenitic stainless steels have higher levels of resistance to most geothermal fluid environments. Titanium, nickel, and high nickel-based alloys generally have the highest resistance to corrosion in geothermal environments.

The presence of deposits and scales influences the sensitivity to corrosion and crack initiation. Mineral scales can have some protective effect, but can also (depending on their thermal and mechanical properties and density of defects, especially micro-cracks), enhance pitting corrosion or under-deposit corrosion, preceding the initiation and propagation of cracks in the substrate. Under geothermal conditions, both carbon and stainless steels can suffer from crack initiation under specific conditions where thick mineral layers form during operation. Efforts are required to understand the stress corrosion mechanisms by considering the effect of

[2]Authors of the chapter: François Ropital, Steve Paterson, Damien Féron

mineral scaling on steel surfaces. Specific electrochemical conditions established at the scale/steel interface can lead to pits and crevice corrosion development. The interplay between the local electrochemical conditions, the nature of the deposited products, specific to geothermal media, and the local plastic deformation and stress states constitute a key scientific question.

In parallel, to select and to develop efficient scale and corrosion inhibitors, a better molecular scale understanding of their protection mechanisms is necessary to establish structure-performance relationships.

Compositionally complex alloys (CCA's) are also a promising new alloy category exhibiting novel properties due to their unique structure. As an example, $CoCrFeNiMo_x$ based high entropy alloys (HEA) could be good candidates for geothermal applications, due to their good resistance to corrosion and mineral scale deposition, and high mechanical and tribological properties. Compositions have to be explored through theoretical modelling, and then validated by experimental property testing to optimise their performance (e.g., corrosion resistance), whilst minimising cost, to facilitate the commercial viability of these new materials in geothermal power plants.

In lower temperature geothermal applications (i.e., 60–100°C) the use of non-metallic materials and alternative lower cost stainless steel options require further evaluation. For the reinjection facilities in these applications, the effects of microbial degradation mechanisms and effective oxygen management need additional attention.

4 | CORROSION IN OTHER RENEWABLE ENERGY SECTORS[3]

4.1 | Wind

There has been a considerable global increase in wind turbine capacity in recent years, especially in offshore marine environments. Significant further expansion of capacity is expected in the coming years, for instance in the United Kingdom there are plans to increase offshore wind capacity fourfold by 2030. The impact of corrosion is an important factor in the design and operation of offshore wind turbine generators (WTGs).

Offshore WTGs have traditionally been based on either monopile structures for shallow water (<30 m), or jacket type structures for deeper water (<60 m), with current offshore WTG sizes up to 10 MW. There is also a growing move to floating structures, such as floating spars, semi-submersibles or tension leg platforms, in 50–800-m water depth with WTG sizes up to 15 MW.

Corrosion protection of these structures is generally achieved through the application of coatings and cathodic protection. The requirements for external coating and cathodic protection in a marine environment are well-understood from the oil and gas industry, but the different commercial drivers associated with offshore wind means that innovative solutions are in demand. In addition to more reliable organic and inorganic coatings to meet a typical design life of 20–25 years, ongoing research and development work is testing the viability of thermally sprayed aluminium (TSA) coatings without sacrificial anodes which would rely on both the barrier and sacrificial properties of the TSA. Another ongoing trial is testing TSA combined with an anti-fouling substance to prevent barnacles attaching to the surface.

Up until 2015 it was assumed that monopile foundations would be water- and air-tight so no internal corrosion protection or corrosion allowance was provided. In reality monopiles can experience seawater and air ingress through hatches left open or seawater leaking through seals for cable openings. There is also a concern about bacterial activity in the enclosed space. For existing monopiles protection can be retrofitted, either using sacrificial anodes or impressed current cathodic protection (ICCP). Research work on sacrificial anodes has, therefore, focussed on testing the aluminium anodes in an acidified internal environment. Work has also considered the possible environmental impact of ICCP in the monopiles, such as generation of chlorine gas. Another area of research concerns modelling the ability of cathodic protection systems to polarise and protect the structures in deepwater.

For structures in an offshore marine environment corrosion fatigue is an important factor because of the fatigue loading generated by the turbines and also wave action. Fatigue of high strength mooring chains for floating structures is also a concern. Much research effort has been directed at understanding corrosion fatigue sensitivity of the structures with the aim to develop less conservative corrosion fatigue models compared to the current design curves published in standards such as DNV GL. Another key area of research involves development of more efficient welding processes, such as electron beam welding, that can produce welds in the very thick structural sections (150 mm) with good weld profiles to reduce stress concentration effects and improve corrosion fatigue resistance.

Wind turbine blades tend to be fabricated from fibre reinforced composites which can suffer leading edge erosion, for example, by water droplets or ice from extreme weather conditions, especially as the blades

[3]Authors of the chapter: Marc Wilms, Gareth Hinds, Steve Paterson, Damien Féron

increase in size. Research work has focussed on the development of more resistant materials and anti-icing coatings such as multifunctional silica nanoparticles incorporated into the resin.

4.2 | Wave/tidal

Solutions for generating energy using wave or tidal sources are much less developed than for wind and currently represent a tiny proportion of the offshore renewables sector. A tidal energy plant was built across the estuary of the La Rance River in Brittany, France in 1966 and produces around 500 GWh/year. To overcome corrosion and corrosion–erosion issues, turbines blades are made from titanium and all metallic parts are cathodically protected by impressed current. Wave energy generators have not yet had sufficient long-term exposure in the marine environment to identify any significant material degradation failures although fatigue performance is a key characteristic.

As these corrosion control options are relatively expensive, current corrosion protection is likely to be achieved primarily through application of coatings. One area of research concerns the requirement for good resistance of coatings to cavitation caused by the movement of the turbine blades. Composite materials are also being considered for wave and tidal applications because of their corrosion resistant properties in the marine environment as well as their high specific strength and stiffness.

5 | CORROSION CHALLENGES IN DECARBONISATION: THE CRUCIAL ROLE OF SAFE BATTERIES AND HYDROGEN TECHNOLOGIES[4]

In the next decade, one needs to reflect on the ambitious climatic plan and rethink energy sources in the industry. Amongst many green technologies, decarbonisation can be achieved by use of gigabatteries for storage of energy produced by renewable sources. Hydrogen technologies can also offer possibilities for a greening world. All technologies applied in energy production from alternative sources encounter in-service durability challenges and thus more research and development activities are needed.

In PV technology, materials degradation can occur in the PV element; solar-powered heat exchanger piping can severely corrode without the application of optimum corrosion inhibitors for high-temperature environments. Battery capability decreases in service due to the different degradation mechanism of electrode materials interacting with a highly conductive and aggressive electrolyte. Internal corrosion of electrode material is directly linked with the safety of the battery pack. Specific corrosion requirements have to be met due to the electrical usage (oxidation, reduction, gas emission). An advanced protection of the materials can be achieved by application of a specific functional coating (i.e., self-healing, nanotechnologies…). At the cathode, materials ensuring more stable cathode electrolyte interphase and surface coatings of anode for more stable solid electrolyte interphase (SEI) together with reduced probability for gas products release, and so forth are required. Coating degradations, growth of Li dendrites, corrosion of aluminium collectors, cementation of copper leading to bimetallic corrosion, and so forth have all been identified as corrosion mechanisms, which shorten in battery life in service (Figure 3). Monitoring the state of health of the electrode material by means of intelligent sensors, identifying critical corrosion parameters in the battery are also key to predict the battery lifetime. All these approaches can help to avoid dangerous events resulting from degradation of the materials and can further improve the safety of the whole battery pack.

Worldwide development of hydrogen technologies brings high demand to increase the resistance of materials against hydrogen embrittlement. This is critical both for transport of hydrogen on a long-distance pipeline backbone across the EU but also in hydrogen storage. Figure 4 shows an example of a green hydrogen source generated in the North Sea providing electricity to various high-demanding energy factories in South Europe, namely steel producing plant, chemical refineries, and fertiliser manufacturing plant.

Advanced materials developed for a new generation of electrolysers need to be tested for safety and increased lifetime. In this regard, the development and implementation of advanced methods for prediction of the hydrogen embrittlement, in both laboratory by analytical methods, and as in-service prototype, are equally important: processes related to degradation of materials when in contact with hydrogen are very complex. Ultimately, corrosion can cause changes in mechanical properties, which can lead to failure or eventually an accident. Hydrogen embrittlement is one of the key and critical issues which need to be checked in all aspects. R&D faces challenges in mathematical and thermodynamical modelling; quantum chemical calculation of interaction of hydrogen with physico-chemistry of materials and/or environmental contaminants will help

[4]Authors of the chapter: Maros Halama, Elizabeth Szala

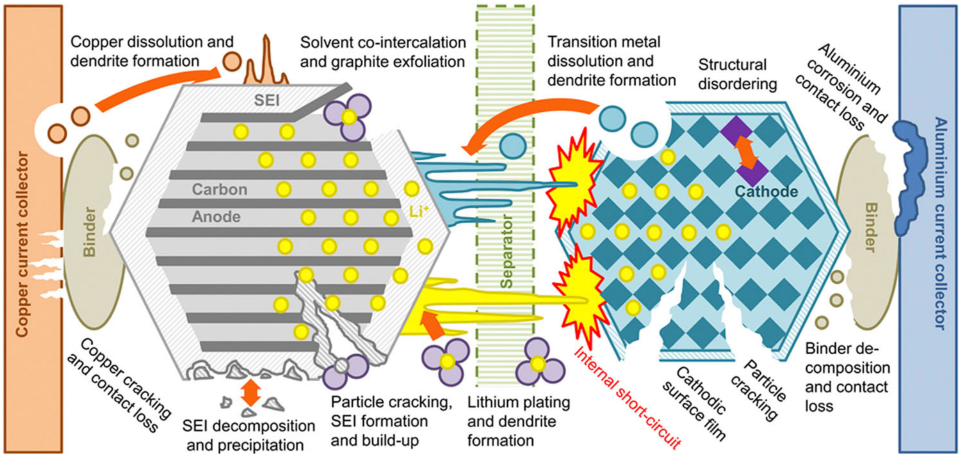

FIGURE 3 Different mechanisms of degradation inside batteries.[5] [Color figure can be viewed at wileyonlinelibrary.com]

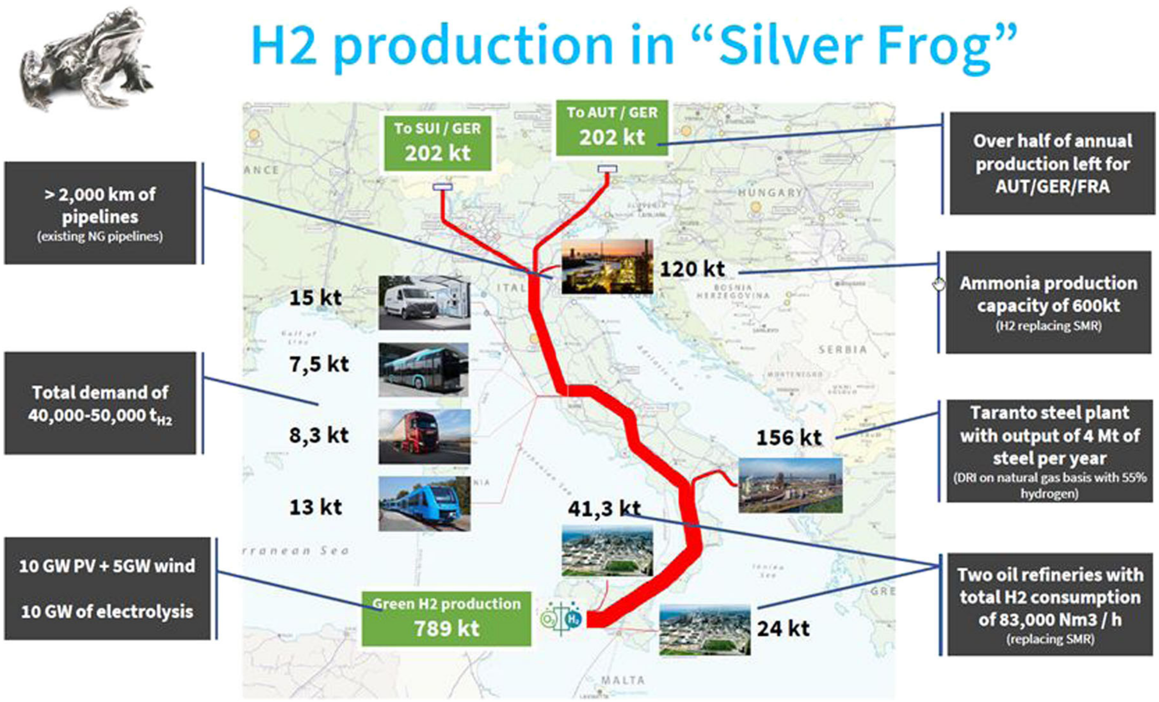

FIGURE 4 Example of a green hydrogen source generated in the North Sea providing electricity to various high-demanding energy factories in South Europe.[6] [Color figure can be viewed at wileyonlinelibrary.com]

in the prediction of the lifetime of the material. Designing special surface coatings resistant to hydrogen permeation is also of high importance.

Hydrogen is the source of energy for fuel cell technologies, which can provide the electricity to transport industry (long-haul transportation, bus, and taxi fleets…) and they are also a solution to ensure electricity to stationary systems due to the very short charge-in time. One of the major challenges of these systems is to provide a material with high corrosion resistance to acidic media while ensuring reasonable conductivity to produce electricity. These two characteristics are usually antagonistic. Diverse coating/material options have been developed but new solutions still need to be discovered to reduce the costs of such products in mass production application.

Before massive investment and such technology deployments, further data acquisitions by computational aided techniques, as well as laboratory experimental results, are required prerequisites to maximise the benefits of new advanced material/coating development together while minimising the negative effect of unknown long-term safety issues that could be encountered while in-service.

6 | CORROSION IN THE NUCLEAR ENERGY SECTOR[5]

With the purpose of maintaining its economic competitiveness while keeping the very high safety standards, the nuclear industry works on how to improve and optimise the performance and durability of its facilities. Hereby, nuclear industry, more than any other, gathers complex corrosion conditions in the whole fuel cycle with a wide range of physico-chemical conditions and materials: various nuclear reactor types (i.e., different structural materials in high temperature water, heavy water, molten salts, liquid metals, hot gases, etc.), reprocessing plants (i.e., concentrated nitric acid), nuclear waste repository (i.e., structural materials in complex underground environments), treatment and concentration process of Uranium-235 (i.e., tetra- and hexafluorine environments), and so forth. It is also important to keep in mind that for the nuclear industry, the consequences of corrosion can be dramatic, one example being the corrosion-induced hydrogen explosion in Fukushima Daiichi nuclear power plant. Consequently, the nuclear corrosion community faces many challenges from the materials conception to the prediction of their ageing under industrial conditions. Some current challenges, representative of the wide range of topics, are listed hereafter.

The extension of the exploitation life of nuclear facilities and more particularly of many light water reactor plants is an illustration of the generally good material selection and technological choices made by the nuclear community during the pioneer period. At the same time, lifetime extension is one of the main challenges which the corrosion community has to face nowadays and during the next decades: not only reliable experimental data is needed, but also the mechanisms behind the corrosion phenomena need to be known (Figure 5). For example, environmentally assisted cracking (EAC) has been one of the main challenges almost since the introduction of boiling and pressurised water reactors. In the view of lifetime extension, EAC and its mitigation still remains an important field for research. Flow-accelerated corrosion, which also has led to large research and re-development programmes and intensive collaborations worldwide, also represents a major issue for the long-term operation of nuclear power plants. Other major challenges are: (i) the prediction of corrosion over millenniums for nuclear waste ageing management, which is a necessity for safe waste storage and for the acceptance of nuclear energy by the public, (ii) the materials behaviour in supercritical water, at high temperature in gas, liquid metals or molten salts for new reactor types of the 'Generation IV', (iii) the materials behaviour at high temperature and under high irradiation flux in gas and liquid metals for fusion reactors, and (iv) the degradation behaviour of materials under shut-down and decommissioning conditions.

Nuclear power is also part of the answer of the global energy challenge: to produce more energy, while reducing CO_2 emissions. It is obvious that extended research on nuclear corrosion prediction and mitigation is a prerequisite for a safe and economic operation of nuclear power plants and therefore an important contribution to the success of this challenge.

7 | MATERIALS AND CORROSION CONSIDERATIONS IN CARBON CAPTURE UTILISATION AND STORAGE APPLICATIONS[6]

Carbon capture utilisation and storage (CCUS) is one technology to mitigate CO_2 emissions from fossil-fuel operated plants and hard-to-cut sectors like steel and cement. Crucial points for a sustainable and future-proof CCUS technology are reliability and cost effectiveness of the whole process chain, including separation of CO_2 from the source, compression of CO_2, its subsequent transportation by pipeline or ship to the utilisation site or the injection site and injection into geological formations, for example, aquifers.

Most of the infrastructure in contact with the CO_2-stream is made of steel components. Depending on the operating conditions (e.g., temperature, pressure, and CO_2-stream composition) suitable steels should be used. The most common CO_2 capture technology utilises amine solvents at temperatures from near ambient to 130°C. Severe corrosion risks are found in these industrial units, and CRAs need to be used at specific locations. Once separated, the compressed CO_2-stream is likely to contain process specific impurities; small amounts of SO_x, NO_x, and H_2S in combination with oxygen and water are most harmful and a challenge to steels.

One approach, as currently preferred by pipeline operators, is to clean the CO_2-stream to levels acceptable for carbon steel commonly used as pipeline and ship tank material. Another consideration would be to use CRAs for CO_2-streams with higher amounts of impurities.

Due to the absence of certified benchmarks for upper limits, systematic experiments with impurities in the CO_2-stream have been carried out reflecting mainly

[5]Authors of the chapter: Stefan Ritter, Laure Martinelli, Damien Féron Partly adopted from S. Ritter (Ed.), 'Nuclear Corrosion: Research, Progress and Challenges', EFC Publications No. 69, Woodhead Publishing, UK, ISBN: 978-0-12-823719-9, 2020.

[6]Authors of the chapter: Ralph Bäßler, Dirk Bettge, Shiladitya Paul, Jean Kittel, Arne Dugstad

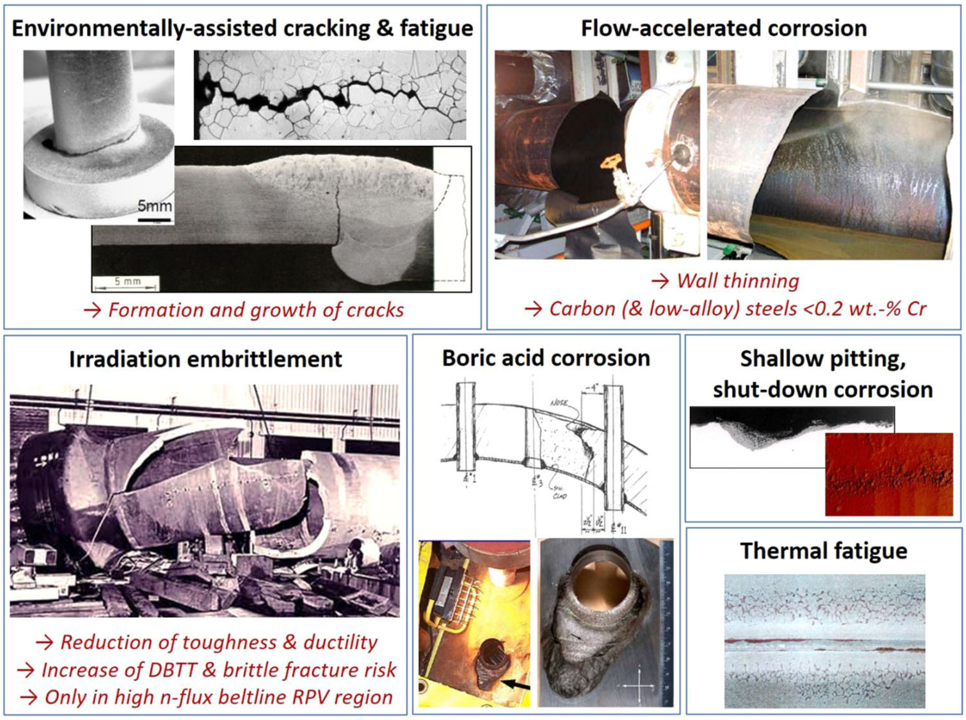

FIGURE 5 Overview on some important ageing and degradation mechanisms in Ni-base alloy, carbon, low-alloy and stainless steel components of light water reactors. [Color figure can be viewed at wileyonlinelibrary.com]

transport and injection conditions. The experiments have shown that condensation of impurities (i.e., H_2O) and their reaction products (i.e., H_2SO_4 and HNO_3) can give corrosive liquid phases for certain impurity combinations and concentrations. This is particularly an issue when CO_2-streams from different sources are mingled.

Publication of results achieved so far will provide a basis for a catalogue of materials and acceptable CO_2-specifications suitable for diverse CCS and CCU applications and contribute to the understanding of corrosion mechanisms. In addition, they will supply background information for standardisation work, as currently performed in ISO TC 265.

8 | SUSTAINABLE PRODUCTION: IMPACT OF REDUCTION OF GREENHOUSE GAS EMISSION IN METAL PRODUCTION AND ITS CONSEQUENCES ON CORROSION PERFORMANCE[7]

The whole life cycle analysis is currently considered when it comes to material development and selection for application in any mean of transportation: automobile, plane, train, and so forth. The energy consumption, the CO_2 emission as well as the recycling process of any material is taken into account at a very early stage of a project Figure 6.[7]

As an example, aluminium production produces ~12 kg of CO_2 per kg of primary aluminium (emissions vary depending on the source of energy).[8] To decrease drastically the CO_2 emission, scrap recirculation in the production loop is a solution. Increasing number of car companies are sorting and redistributing the scrap to the metal suppliers to close the loop to re-inject the materials in the process, hence decreasing the energy consumption for aluminium production. The target of aluminium industry is to produce aluminium alloys commonly used for automotive application based on remelted aluminium and post-consumer scrap. An extrusion ingot with min. Seventy-five percent post-consumer scrap can reach a low carbon footprint of 2.3 kg CO_2/kg Al, comparable to production of steel.[9]

This change in production process induces the presence of trace elements (i.e., Cu, Zn, Pb, Sn, In, Ga, etc.) in the alloys that to some extent will influence the corrosion properties of the alloy. This is because the corrosion mechanisms are to a large extent controlled by the microstructure of the alloys. The trace elements will also have influence on the surface finishing properties after anodising.

Challenges in research and development lie in the variation in compositions within an alloy family: corrosion properties should not be jeopardised by the

[7]Authors of the chapter: Elizabeth Szala, Jan-Olov Nilsson

FIGURE 6 European End of Life (EOL) Vehicles Directive, 20151. [Color figure can be viewed at wileyonlinelibrary.com]

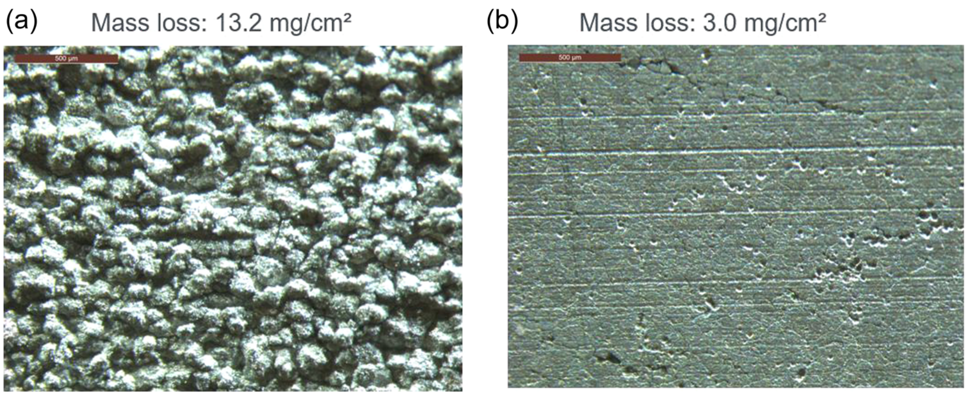

FIGURE 7 Surface microstructure after IGC test-ISO 11846, on casts A and B from alloy EN-AW6063. [Color figure can be viewed at wileyonlinelibrary.com]

variability in the trace element concentration. Figure 7 shows difference in corrosion performances of two different casts based on 100% recycled aluminium with some variation in trace element concentration.[10]

9 | LIGHT-WEIGHT DESIGN IN TRANSPORTATION TO REDUCE CO_2 EMISSIONS: IMPACT ON CORROSION PERFORMANCE[8]

Due to greenhouse gas (GHG) emission regulations, the transport industry is facing the challenge to improve fuel economy. In 2018, in Europe, 20% of the GHG emission was related to transport. Reducing vehicle and aeronautic structure mass as well as developing alternative energy vehicles, thereby reducing environmental impact are possible solutions and inevitable to improve fuel economy. Weight optimisation is a substantial pillar also for decarburisation and green aviation approaches in combination with clean energy solutions like sustainable aviation fuels, hydrogen propulsion and solar powering. Lightweighting has become one of the most important aspects to consider in the design and manufacture of modern mean of transportation. All the aforementioned factors have a significant impact on materials selection and usage, and corrosion is a crucial consideration.

Most manufacturers are reducing structure mass. For instance, in automotive industry, in the last decades several advanced materials have been selected such as advanced high strength steels (AHSS), ultra-high strength steels (UHSS), press hardened steels (PHS), aluminium and magnesium alloys, and composites (Figure 8). AHSS, UHSS, or PHS can be subjected to delayed fracture when in-service. Factors affecting the risk of hydrogen embrittlement of high strength steels due to corrosion-induced hydrogen entry in service conditions are studied thoroughly to open new applications. For aerospace application high-strength copper and zinc containing aluminium alloys with higher corrosion protection requirements and titanium alloys are the main structural materials beside the already mentioned high-strength steels and composites. CFRP materials are increasingly competing with aluminium alloys in future aircraft components. Recently developed new aircraft designs which have entered into service like the Airbus A350-XWB or the Boeing 787 comprise already 50 wt% and more of CFRP while the aluminium share is decreased down to around 20%. Titanium content is slightly increased to about 15% at the expense of aluminium due to its better electrochemical compatibility with CFRP.[11,12]

To provide corrosion protection to steel structures, various coatings have been developed: Al–Si coatings for

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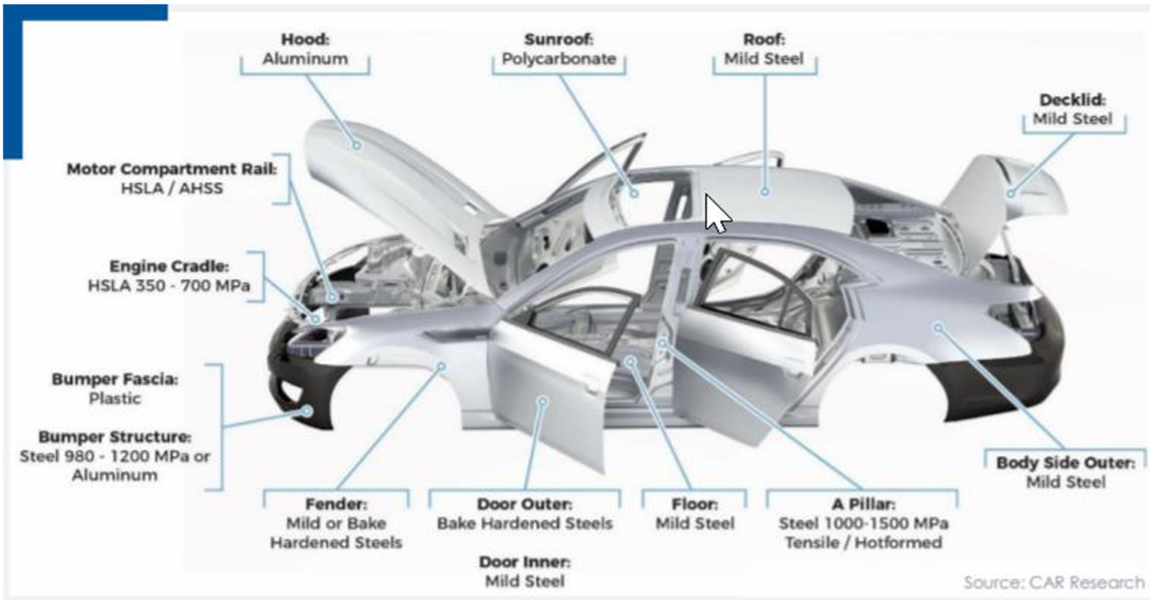

FIGURE 8 Example of a multi-material body-in-white, Alliance Project Horizon 2020 (2016–2019).[13] [Color figure can be viewed at wileyonlinelibrary.com]

PHS, Zn–Al–Mg coating to reduce up to 50% the thickness of galvanised layers for the body-in-white. Zn–Ni as well as lamellar zinc coatings have substantially improved corrosion resistance of fastening products and smaller car parts. Aluminium usage is expected to grow from 150 to 220 kg on average per vehicle by 2025[14]: various grades with different mechanical properties can be chosen for their better formability or higher strength.

Many developments have been conducted in the last decades to meet REACH legislation and replace traditional surface treatments. Various novel coatings as well as pretreatment technologies have been implemented in transport industry. Tartaric/sulphuric anodising for aerostructures and Cr(III) conversion coatings for vehicles' trimmed parts and accessories are applied and have replaced harmful Cr(VI). The conventional phosphatation process before cataphoretic painting of car bodies is gradually being replaced by thin-film pretreatment technologies, for example, silane and/or Zr-based. These products no longer use hazardous substances but and also drastically decrease water and energy consumption in production. In view of extremely tight requirements on product longevity, these changes put an enormous pressure on reliability and further development of accelerated corrosion tests used for long-term prediction of performance and verification of the new solutions.

Carbon fibre-reinforced polymers (CFRP) have also been developed in the last two decades for the aerospace as well as for the automotive industry: they present a high specific strength and are promising lightweight materials. Although the polymeric resins may have some susceptibility to degradation, generally, CFRPs are considered inert and corrosion resistant. However, when reinforced with carbon fibres, there may be corrosion issues that arise when joining carbon fibre composites with metals: CFRPs are electrically conductive and electrochemically very noble in comparison with most metallic materials used in the transport industry. Therefore, when a metal is inappropriately joined with CFRP (i.e., an electrical connection is made without isolating the parts, or without appropriate long-term protection), the metal is susceptible to suffer galvanic corrosion. When coupled with a fastener or bolt, the situation worsens since a large surface area of CFRP is coupled to a small area of metals. In these cases, the galvanic corrosion rate may accelerate due the high cathode to anode surface area ratio.

All these materials are selected and combined in a complex multi-material structure where galvanic coupling becomes a challenge in these extremely low-weight concepts: CFRP to metal, aluminium to steel or titanium (different technologies for coatings on fasteners to ensure durability of the multi-materials structure and avoid the high cathode to anode surface area ratio). Especially in the case of Mg alloys the very high risk for galvanic corrosion is often the blocking point for structural application in aviation and automotive. In addition, the type of joining method plays also a strong role in the multi-metal design concept: the same anticorrosion measures will not be applied on a welding combination as on a mechanic bonding (i.e., fastening, riveting) or on an adhesive bonding system.

10 | SUSTAINABLE POWER ELECTRONICS BY IMPROVED ROBUSTNESS AGAINST CLIMATE STRESS[9]

Society is under the influence of the global megatrends of climate change and scarcity of resources, shifting of economic powers, urbanisation, demographic change, and digitalisation. To successfully counter these changes and even shape them positively, power electronics has taken a key role in all fields of society. To meet the increased demands on the robustness and reliability of power electronic components and systems, comprehensive knowledge of their corrosion behaviour is necessary. However, corrosion mechanisms are highly complex. They depend on the materials, the environment and the respective protective measures. Accordingly, efforts must urgently be taken up in the most diverse research fields to create a comprehensive and secured data situation.

Due to the increased demands on power electronics, corrosion research in the field of electronics and electrical engineering will have to take an increasing role.

For example, the hydrogen economy will play a decisive role in the alternative energy concepts and the adequate storage of this energy, which is not generated at the time of consumption. Here, in the initial phase, proportions of pollutant gases that cannot yet be estimated will also accompany the green hydrogen, favour corrosion reactions and thus in turn severely limit the usability or service life of the components used. Exactly here are also long and especially reliable service lives necessary to create benefit in terms of application technology.

In the field of power electronics, Europe has a very strong position in industry and research. To maintain this position, it is important to make optimal electrical use of the power electronics components (especially semiconductor components such as Si-IGBTs or SiC-MOSFETs). However, this increases the operating loads and electrical sensitivity of the modules. This should be compensated by improved corrosion protection and thus minimised leakage currents.

The upcoming modernisation of the railway, from the track to the smart goods wagon, also requires very good corrosion protection due to the often-harsh environmental conditions to exploit the economic benefits through the best availability of the systems. Intelligent housing solutions in particular will play a key role here in the future.

To achieve the reliable implementation of the mentioned social goals as well as increased sustainability (energy saving, resource conservation…) by increasing service life and efficiency, corrosion research must address the following fields:

- Aluminium and copper corrosion at chip level, that is, the influence of moisture and the smallest impurities on power semiconductors.
- Corrosion protection of the so-called aluminium guard rings by glass or polymer passivations to keep the reverse voltages of power semiconductors stable.
- Prediction of corrosion processes, especially from the so-called anodic migration phenomenon (AMP) and electrochemical migration in complex environments such as wind power plants, railway systems or in electromobility.
- Development and optimisation of high-voltage and high-temperature resistant corrosion protection systems.

This results particularly in the following research topics:

- Expansion of knowledge of the role of pergulating networks in the AMP in potting or epoxy moulding compounds.
- Development of alternative high-voltage protection systems such as parylene, ALD and similar ones for so-called sandwich modules, which enable smaller and more universally applicable power electronics.
- AMP-resistant solder resist and protective coating systems for moisture-robust and ageing-resistant power electronics.

11 | CORROSION IN THE OIL AND GAS PRODUCTION SECTOR[10]

The production of oil and gas faces a large number of corrosion challenges that need to be addressed in the current cost-conscious climate. The total costs of corrosion in this sector is estimated at US$ 1372 billion per annum. The severe consequences of a potential material failure—which could result in a release of flammable and often highly toxic products—put high demands on the integrity of production facilities. In combination with the size of the industry and its production facilities, optimisation of corrosion mitigation strategies and development of new

[9]Authors of the chapter: Helmut Schweigart, Ramona Krieg, Thomas Harder This position paper is jointly supported by GfKORR - Society for Corrosion Protection e. V. - Working Party 'Corrosion and Corrosion Protection in Electronics', DVS - Deutscher Verband für Schweißen und verwandte Verfahren e. V., ECPE European Centre for Power Electronics e. V.

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technologies are key for safe and cost-effective oil and gas production in the future.

The main challenges are the wide variety in corrosivity of the production streams, the harsh environmental conditions at often remote production locations, the large number of different failure mechanisms that are applicable, and high mechanical and wear demands. Next to 'weight loss corrosion' modes, various types of environmentally assisted cracking related to hydrogen make the corrosion challenges complex.

Carbon steel and low alloy steels are the work-horse materials, however, to manage corrosion rates to an acceptable level, injection of chemical corrosion inhibitors in the production stream is required in almost all cases. Deeper wells and related subsea applications with the associated higher pressures and temperatures, sour systems and environmental considerations, demand improved corrosion inhibitor chemistries. With the high profile of sustainability in the oil and gas industry, the inhibitor suppliers, with an estimated market value of US $ 8 billion, along with the rest of the industry have to adapt. Research is focused at environmentally acceptable products with high level of biodegradability and low toxicity, as well as more concentrated products to reduce carbon emission associated in the supply chain. This is part of wider move towards a 'greener' future.

In many cases conditions are so corrosive that carbon steel or low alloy steels with inhibition cannot be used. In these cases, stainless steels or even nickel base alloys are applied. Given the higher costs of these alloys, development of less high-alloyed stainless steel with more favourable properties and lower cost are ongoing. The development of application-specific test methods is key, as these can extend the application limits of these alloys and thus avoid over-conservatism. For this, multidisciplinary programmes are required including thermodynamic modelling of the environment the materials are exposed to as well as process flow modelling.

New oil and gas discoveries typically involve more demanding conditions: deeper wells, more corrosive conditions, higher temperatures and pressures and challenging locations. Development of better performing materials is required, which requires a continuous effort to be able to meet project demands. More effective material use can be achieved by applying highly corrosion resistant metallic liners or claddings, polymer liners, or advanced high-performance coatings on the carbon steel substrate material. Further development in this area is ongoing and impactful. Developments in fibre-reinforced polymers have great potential. This is also the case for improved installation methodologies, including novel joining techniques. Numerous developments are ongoing in these areas and will be key to safe and economically viable installation and operation in the future. Specific applications require strain-based design, which enhances corrosion cracking mechanisms and needs a better understanding. Other challenges are ultrahigh H_2S exposure, where applying fugacity rather than pressure is being introduced into the industry to assess materials behaviour more accurately. Key research programmes are ongoing on novel corrosion monitoring techniques, nonintrusive inspection technology and improved corrosion management strategies, all aimed at increasing technical integrity and safe operation.

To reduce the carbon footprint significant and growing research efforts are directed to processes to produce clean, synthetic fuels via chemical or electrochemical processes. Different options are being investigated, which use green energy and often apply CO_2 as a source. A common aspect of these processes is the very corrosive conditions for construction materials. When scaling these processes up from laboratory to pilot plants and finally production facilities, corrosion is one of the main challenges.

Transfer of knowledge, experience and expertise from the oil and gas sector to low carbon energy technology sectors such as wind, hydrogen, geothermal and carbon capture and storage is also an important factor in facilitating the energy transition.

12 | INFRASTRUCTURE—CORROSION OF REINFORCED CONCRETE[11]

Reinforced concrete is the worldwide mostly used building material for our infrastructure. It is flexible, robust and economic. While the compressive strength of concrete is quite high, the tensile strength is very limited. Therefore, usually steel reinforcement is used to create a powerful composite material. However, due to different mechanisms these reinforcements often corrode. Especially when chlorides are attacking the structures the corrosion rates can be very high and result in serious damages up to partial or complete collapses. Due to the increasing age of our infrastructure the costs for maintenance is also increasing. For the traffic infrastructure in industrial countries about 50% of the maintenance costs are directly related to corrosion. The costs for corrosion of reinforced concrete structures, for example, in the USA are estimated to be in the range of US$ 20–40 billion.

[11]Author of the chapter: Michael Raupach

The mechanisms of corrosion of steel in concrete are very complex and due to the huge number of influencing factors from the materials for concrete and reinforcement as well as environmental factors, corrosion of the reinforcement is difficult to quantify and predict. Therefore, the corrosion evaluation and selection of protection and repair measures needs to be carried out individually for each concrete structure. Due to lacking understanding of the corrosion and protection mechanisms, in practise decisions on the best maintenance and repair methods are difficult. Only if the durability of all relevant repair and protection methods is known, reliable life cycle-oriented management is possible. Therefore, modelling of the durability regarding corrosion is an important topic. Effective sensor-based monitoring systems are required to support inspection and supervision of the status of buildings and prevent unexpected corrosion problems. These will be integrated in digital building models in future, allowing an effective building maintenance.

Another important corrosion topic for the future results from the clear trend, that the traditional cement as binder for concrete will be replaced by materials with lower carbon footprint. In this context there is an urgent need to investigate how these new binders influence the corrosion behaviour of the reinforcement and durability of concrete structures and which protection measures are required.

Intensifying research in the fields mentioned above is an important element to reduce the actually huge costs for corrosion of our infrastructure.

13 | CORROSION AND ADDITIVE MANUFACTURING[12]

Metal additive manufacturing (MAM), a process by which complex multifunctional metal parts are produced in a layer by layer fashion, is considered one of the enabling technologies for Industry 4.0. This technology has attracted a great deal of attention in recent years and has found numerous applications in industries such as medical implants, energy, aerospace, and automotive due to the fact that it allows near net-shape manufacturing of geometrically complex parts such as lattice structures and three-dimensional structures with undercuts or cavities. Nowadays, a great number of metals and alloys can be processed by additive manufacturing techniques, depending mainly on the availability of the raw materials as appropriate feedstock for the MAM processes.

Due to the special conditions associated with MAM (for instance, small melt pools, rapid solidification, and the use of pre-alloyed metal feedstock), a very fine microstructure with unique directional growth features far from equilibrium is generally obtained. This distinctive microstructure, together with other special features and microstructural defects originating from the additive manufacturing process (such as relatively high surface roughness, porosity, internal residual stresses) are known to greatly influence the performance and corrosion behaviour of these materials. Some studies have already been dedicated to investigate the impact of microstructure, post-thermal treatments, surface roughness, and porosity on the corrosion resistance and corrosion behaviour of additively manufactured (AM) metal parts. However, varied results (and in some cases contradictory) have been obtained. Moreover, several open questions still remain, needing more dedicated investigation. Variations in factors such as process parameters, scanning strategy, MAM technology used, power source and feedstock characteristics, or even differences in the size and number of samples fabricated during the MAM process could induce differences in the cooling rates and thermal history during the layers cycles. These variations in the thermal history of the printed part can affect the microstructure and formation and distribution of defects in it, and consequently the properties and performance of the material. However, this interrelation is not yet well understood. A better understanding of the effect of these parameters as well as the synergistic effect of these factors and post-thermal and post-surface treatments on the microstructure and corrosion performance of AM metallic structures is crucial for the further development and application of MAM technologies. Moreover, most of the works conducted to date investigating the corrosion behaviour of AM specimens have been dedicated to parts fabricated by laser-powder bed fusion technology. Dedicated studies on the corrosion resistance of metal parts fabricated using other MAM techniques are highly needed.

In addition to the need for a better understanding of the corrosion behaviour of AM parts, another major challenge concerns the mechanisms for corrosion protection of these materials. While few works have been dedicated to study the anodising performance of AM Al- and Ti-based alloys, other surface treatments such as electrochemical conversion, and electroplating have been largely ignored. Moreover, those preliminary studies on the anodising behaviour of AM materials have highlighted the enormous impact of the special microstructure and defects resulting from the MAM process on these surface treatments, as well as the need for further investigations in this area for better understanding the relation between MAM process condition, microstructure, surface treatment mechanism, and performance.

[12]Authors of the chapter: Reynier I. Revilla, Iris De Graeve

14 | SELF-HEALING COATINGS[13]

Traditionally, protective organic coatings are applied to a wide variety of metal (alloys) when used in practice under corrosive conditions. Such applications may vary from offshore structures, bridges, aircraft, automobiles to microelectronics, process industry, windmills and many more. The main function of these coatings is to form a physical barrier to aggressive species present in the surrounding medium to reach the coating-metal(oxide) interface. Such protection may hold well in case of an intact coating. However, coating defects by mechanical scratching, punctures or delamination are common to occur during manufacturing, assembling or the service lifetime of products and structures. In that case an active protection mechanism should kick in to limit the corrosion attack at these coating defect areas. To this aim, several active self-healing coating concepts have been developed to provide effective long-term protection. These concepts can be considered as standalone protection systems or combined within the same coating system in different layers or carriers within one coating layer.

Among the self-healing coating systems, those based on leaching corrosion inhibitor effects are of paramount interest and have been actively developed during the last decades. A range of encapsulation approaches is reported to create nano-(micro-)containers of corrosion inhibitors capable of storing the active compounds and providing their prolonged or even controllable release on demand. Nevertheless, most of the research done in the direction of development of new active protective coatings follows a trial-error approach rather than a systematic way of coating design considering all the important factors such as compatibility between inhibiting pigments and coating matrices, kinetics of inhibitor delivery to a relevant defect under relevant conditions and reversibility of the inhibition function. This is often the reason why most of the systems demonstrate a level of performance which does not meet industrial standards for specific applications. In contrast, a systematic approach based on fundamental understanding of different components as well as the full active protection system seems to be the only way which can lead to successful results and their fast implementation in industry.

Finding new efficient corrosion inhibitors for specific metallic substrates utilised in variety of service conditions is one of the key issues. This task cannot be effectively done using only experimental approaches, considering the nearly endless chemical space of the potential candidates and must be accompanied by combination of physics-based and data-driven modelling approaches. The digitalisation of the whole active protective coating design process including the adequate cyclic aging tests and its combination with a deeper understanding of the self-healing mechanisms at the different realistic types of defects is a way to move forward towards reliable self-healing coatings.

15 | CORROSION OF METALLIC BIOMATERIALS[14]

Metallic materials have been used as implants in dentistry, in orthopaedics and as cardiovascular stents for decades. However, corrosion of metals in the human body is a key factor, which defines the durability of the implant and biocompatibility. The corrosive degradation can compromise the mechanical properties of metallic implants but also can lead to release of significant amount of metal cations causing undesirable biological effects and often rejection of the implant. Considering the aggressiveness of body fluid environments, alloys forming a strong passive film are required for permanent implants, such as Ti alloys, stainless steels, and CoCr alloys, just to mention a few. However, cyclic loads and macro-/micro-wear can cause a local depassivation and initiation of localised corrosion. Such tribocorrosion not only can enhance release of metal cations but moreover lead to formation of wear particles. For Cr-containing stainless steels and CoCr alloys, concerns have moreover been raised on possible release of toxic/carcinogenic Cr(VI) under oxidising conditions; this issue has not been fully resolved. In general, not only the amount of corrosion but the chemical speciation of the dissolved species from implant alloys is decisive for their effects on the biological surroundings. Surface modification of the permanent implants was recently pursued as the main strategy to improve the corrosion performance and the biocompatibility of such devices. The set of technologies from polymer coatings to porous oxide layers formed via plasma electrolytic oxidation approaches has been reported. Nevertheless, the abovementioned issues are far from being completely solved and require additional research and development efforts towards surfaces with higher corrosion resistance, but also offering additional functionalities such as drug delivery and enhanced osteogenecity.

A principally different paradigm is used in the case of bioresorbable metallic implants, which are supposed to deliver the load-bearing function only for a limited period of time during healing. The corrosion process in such cases should not be fully prevented but rather controlled to match the healing dynamics. The most developed resorbable metallic implants are based on Mg alloys, although the corrosion rate of such materials is

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often too high and the generated hydrogen might also cause additional complications. Moreover, Mg alloys typically show a rather nonuniform corrosion morphology that could locally lead to loss of mechanical integrity (especially for stent applications, due to the small dimensions of the stent struts). The biocompatible metals with lower corrosion rate in body fluids such as Fe and Zn are also currently actively investigated. For these materials the major cathodic reaction is oxygen reduction reaction (and not H_2 evolution); this is considered an advantage as compared with Mg alloys. However, in this case the degradation kinetics is often too slow leading to unacceptably extended bioresorption periods. Both the high corrosion rate of Mg alloys and the slow degradation rate of Zn- and Fe-based systems constitute important future challenges to be overcome in next decade via alloy design and surface modification technologies.

Further improvement of the implant design in terms of forming porous scaffolds for a better fixation of solid implants to the surrounding bone tissues or constructing modular implants for patient specific requirements create additional corrosion-related issues such as galvanic effects and enhanced tribocorrosion.

Design of the new metallic materials with desirable corrosion resistance as well as development of the new functional surface treatments to control the degradation kinetics require adequate measurement techniques and testing protocols. Recently strong differences between in vitro and in vivo degradation kinetics and mechanisms have been documented for many metallic materials, especially the degradable ones. A large variety of different corrosive media has been reported for evaluating corrosion performance, ranging from simulated body fluids representing the inorganic components of blood, to more complex electrolytes including organic and/or biological components such as amino acids, proteins, and cells. Still a reliable correlation of laboratory testing with in vivo results is lacking. This indicates the urgent need for new verified corrosion test protocols representing in vivo conditions.

16 | PROTECTION OF CULTURAL HERITAGE[15]

The ubiquitous use of metals throughout our past makes their preservation vital for the retention and study of our cultural heritage. Their use in objects, tools, machinery and structures, from early times to the modern day, explains their presence in all types of museum collections, from archaeology through to modern day science museums (Figure 9). To understand how metals have survived and explain the changes they have undergone in various climates and contexts including burial in soils, enclosure in tombs, marine immersion and exposure in atmosphere, requires research into their historical and cultural context, composition, technology, and corrosion. This knowledge is used to underpin the design, development and quality of evidence-based treatments that aim to control or prevent ongoing corrosion. Collaboration between corrosion scientists, metallurgists, coatings technologists, heritage scientists, and conservators can produce the synergy necessary to fulfil this goal, provided each is able to identify their potential to contribute.

This requires a holistic understanding of the thought processes involved. Context and function will influence ethical decisions regarding acceptable procedures for preserving heritage metals. While application of new coatings, complete removal of corrosion and replication may be corrosion control options in the commercial world, they are often ethically unacceptable within heritage. Preserving evidence of appearance and use are often paramount considerations, yet this evidence could be present as a corrosion product layer, making its retention essential. Factors such as uniqueness and originality also influence decision making.

There have been a number of successful standalone contributions and collaborations to date. Elucidation of corrosion mechanisms taking place over millennia has informed on the effectiveness of treatment methods such as washing electrolytes out of fragile archaeological iron. Inhibitors that stabilise copper alloys, while retaining aesthetically pleasing patinas have had their effectiveness quantified. Management regimes for storage and display of metals in museums have benefitted from improved understanding of how relative humidity influences the corrosion rate of metals retaining corrosion products and patinas. Outdoor displays involving vehicles, ships and militaria have employed research into surface preparation and coating technology to protect against their corrosion. New testing is underway for green alternatives when using inhibitors. These success stories and others not identified here, can only be replicated by increasing partnerships between scientists within academia, researchers in commercial contexts, conservation scientists and heritage professionals engaged in cultural heritage protection.

[15]Authors of the chapter: Delphine Neff, Johan Tidblad, David Watkinson, Sabrina Grassini

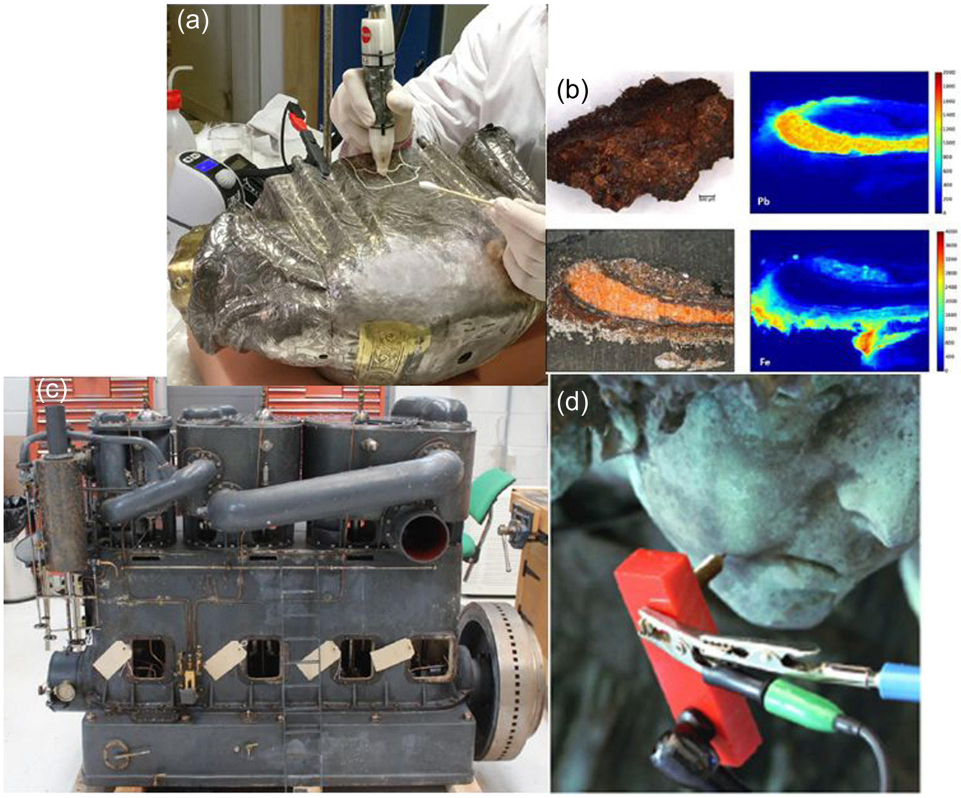

FIGURE 9 Examples of corrosion cases in the cultural heritage field.[15] [Color figure can be viewed at wileyonlinelibrary.com]

17 | FINITE ELEMENT MODELLING AND ARTIFICIAL INTELLIGENCE FOR CORROSION PREDICTION THE WAY TO GO[16]

Nowadays, production companies in the automotive, aviation and other high-tech industries continuously try to improve their products by making their products more sustainable, of higher quality, and more customisable. Consequently, with increased pressure on 'time to market', the need for modelling tools have increased drastically within a relatively short period and they have been the subject of a continuous improvement process. Advanced modelling tools are applied for studying aerodynamics, stresses, pressures, thermal behaviour, and design of the bonnet utilising computer fluid dynamics, finite element modelling (FEM), structural analysis,[3] and multi-body dynamics. These modelling tools provide more detailed information than experimental investigations and are often much faster and substantially cheaper. Unfortunately, at this moment in time, design engineers have limited software tools available to support them when it comes to surface phenomena taking place on the materials that are essential for the long-term sustainability of the finished products, such as corrosion and protection choices for lifetime extension. Very few commercial software exists but their approach leads to oversimplification resulting in limited reliable predictions for particular cases. The lack of corrosion forecasting tools is limited because modelling this phenomenon is extremely challenging, especially when taking the actual conditions, the objects are operating under, such as condensation and evaporation of the electrolyte into account as is the case for atmospheric corrosion. Currently, metal-based products are developed with lifetime requirements ranging from 10 to 100 years, depending on its exposure to the environment, bringing up the question about what the correct corrosion ageing process is. Today, corrosion estimation is usually an extrapolation derived from oversimplified experiments, combining accelerated and long-term field testing. The limitation of field tests is that they take several years (at least 5–10 years), whereas accelerated corrosion tests only provide a superficial classification of the material ranging from 'unacceptable' to 'excellent' in a reasonably short time. Apart from this being a rather crude differentiation there is no clear link between actual corrosion conditions and these accelerated test regimes but more of a best practice' situation

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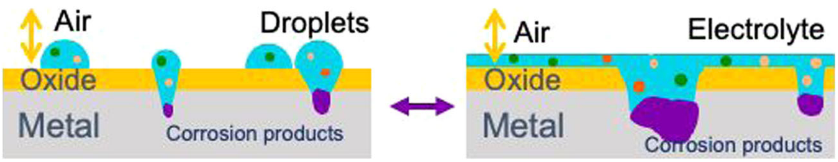

FIGURE 10 Schematic representation of the essential subcomponents of atmospheric corrosion. [Color figure can be viewed at wileyonlinelibrary.com]

based on past experiences. All in all, it can be concluded that current corrosion tests are a sort of a black-box evaluation, where it becomes difficult to link the testing procedure to the behaviour of the products beyond a certain specified environment. As a result, when it comes to corrosion (e.g., see Figure 10), there is a complete lack of reliable long-term assessment. FEM modelling and AI aim to achieve the required paradigm shift in the metal's lifetime prediction, thus we need a radically different research approach. The critical issue is that most corrosion experiments in fundamental research are performed 'in solution' under the assumption that the electrolyte layer is thick enough to approximate it as 'infinite', ignoring significant local corrosion effects introduced by dynamic electrolyte dimensions caused by droplets and puddles.

To reach accurate numerical models, we first and foremost need to abandon this 'infinite' and 'stationary' approximation and consider dynamic and finite electrolyte dimensions on the metal surfaces. With this FEM modelling we explore this key area by taking advantage of the interaction between FEM and experimental approaches. A fusion between reliable experimental and accurate modelling tools will make it possible to describe and predict the corrosion under dynamic electrolyte geometries ranging from µm's (droplets) to mm's (continuous film). assisted by a two-way interaction with numerical tools, key insights into this dynamic atmospheric corrosion process can be isolated and translated into an accurate and ever-improving prediction tool. An accurate and real time evaluation of atmospheric corrosion provides an important guide to materials selection and engineering design for corrosion mitigation. Monitoring sensors have been used in vehicles and bridges to track the dynamic process of atmospheric corrosion and to understand how such a process is influenced by the complex environmental parameters. Monitoring sensors are providing large data sets typically suited to be fed into machine learning tools. Making use of for example simple electrochemical sensors prediction models can be derived from AI approaches. If we can connect the FEM model with the AI approaches and add DFT models we speak about multiscale models. By doing that we will be able to reach out for reliable prediction models. There is still a long but a necessary way to go and it will be only possible by collaborative research.

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18 | CORROSION AND ENVIRONMENT: THE RELEASE OF METAL IONS TO THE ENVIRONMENT[17]

Metals are vital for a modern society and their sustainable use is essential. The environmental footprints of metals and alloys must be maintained at a fair level with no adverse effects on either human health or the environment. Since the beginning of the 21th century the global awareness of such risks from a life cycle perspective have rapidly emerged worldwide. This has resulted in global commitments related to the use of chemicals (including metals) via different regulatory measures. Such measures include the implementation of the Globally Harmonised System of Classification and Labelling of Chemicals (UN GHS, 2015) and the implementation of the REACH framework within EU (Registration, Evaluation, Authorisation and Restriction of Chemicals, EU, 2006).

To meet the increasing environmental concern, research activities at KTH Royal Institute of Technology have explored the diffusely dispersed and migrated metals from a wide variety of metallic surfaces, ranging from bulk to nanoparticles. This multidisciplinary research programme evolved in close collaboration with toxicologists to other areas such as food, implants and medical materials, and general human exposure. Underlying mechanisms and relations to bioavailability and surface oxide characteristics have been elucidated in a multitude of environments. Studies have been performed to correlate changes in material properties and surface characteristics to the extent of diffusely dispersed and migrated metals and their connections to environmental fate and toxicity. More recently the focus has been on

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aspects of relevance for food contact, implants, medical devices, consumer products, high-touch surfaces, and so forth.

This study has resulted in some 80 scientific publications so far, furthermore in findings directly applicable in risk management and assessment, as well as in the elaboration of novel methods and operational protocols and improved standards. Quantitative bioaccessibility data has been generated for a large number of metals, alloys, metal oxides, pigments, and so forth and used by national and international metal consortia in the mandatory registration dossiers, required within the framework of REACH to register chemicals and products, based on, for example, Fe–Cr alloys, Mo metals, Fe–Si alloys, Ag, Sn, and Sb. Increased knowledge has enabled relevant countermeasures to be taken and provided necessary knowledge for safe-by-design measures.

Two key publications are:

- Y.S. Hedberg, I. Odnevall Wallinder, Metal release from stainless steel in biological environments – a review, Biointerphases – special issue on *Ions and Solvation at Biointerphases* **2016**, *11*, 018901-1, https://doi.org/10.1116/1.4934628.
- X. Wang, J. Noel, I. Odnevall Wallinder, Y. Hedberg, Metal bioaccessibility in synthetic body fluids - a way to consider positive and negative alloying effects in hazard assessments, *Materials & Design* **2021**, *198*, 109393.

19 | CORROSION ISSUES AND RESEARCH PROGRESS OF GREEN AND LOW CARBON ENERGY IN CHINA[18]

19.1 | Background

Global warming requires green and low carbon energies which have been strengthened during the last 10 years. For a long time, fossil energy has been dominant in China and reaches up to ~75%. To adjust its energy mix, China continues to strengthen the development of green and low carbon energies and cut back on coal power. Although the total energy consumption increased more than three times in the last 20 years, the coal power decreased 20%. Over the past decade, the amount of nuclear, wind and solar power generation has been increasing, and the development of urban waste energy is also accelerating.

The annual investment in 2020 for renewable energy such as solar PV, wind power, hydropower, concentrating solar thermal power, solar water heating in China ranked top one in the world. At the end of 2020, the renewable power capacity (both including and excluding hydropower) in China also ranked top one in the world. Similarly, the biopower, wind power, solar PV capacity in China ranked the top one also. Moreover, the solar water heating collector and the geothermal heating output also ranked the top one in the world. As an example, 10 years ago, solar energy was almost nothing in China, but by 2020, solar energy accounted for about one-third of the world. According to the estimation, China will continue to cut the coal power from above 55% to less than 20% in total and to increase the renewable energy from less than 10% till 40% by 2050, and this will be a big ambition.

As the corrosion scientist and engineer, we should understand that corrosion affects the safety of engineering structures, the reliability of energy equipment, and strongly affect the energy cost. Much more research work should be done.

19.2 | Corrosion in solar energy in China

There exist three kinds of ways to utilise solar energy such as solar thermal, solar hot water and the solar PV. The solar thermal has ~30% efficiency which requires direct sun and the heats fluid in pipes boils water to drive steam turbine. This is cost-competitive energy. The efficiency of solar hot water could reach up to 50% which is easier to use for family in home. Although the solar PV has relatively lower efficiency, about 15%, however, it could obtain electricity directly in home and cost effective which also is popular in the world. There are three main types of solar PV, namely monocrystalline silicon, polycrystalline silicon and amorphous silicon (amorphous), which have different efficiency and cost.

China's solar energy has grown rapidly in the past decade. However, there are still some corrosion problems so far.

(1) Aging of PV module. To reduce the energy cost, the lifetime of solar PV module is from 5 to 25 years. There are some aging phenomena such as PID effect, snail line, EVA yellow stain, aging crack of backboard, and so on. In China, we have found that after monocrystalline silicon PV modules are serviced, solar PV modules have aging phenomena, such as snail line. Once the snail line appears, the maximum power decreases by more than 23%, which seriously affects the efficiency and increases the energy cost.

[18]Author of the chapter: En-Hou Han

(2) Corrosion of supporting system. All solar PVs have support systems, including metal supports, pile components and grounding systems, with a service life of 25+, which is the same as that of solar PVs. The supporting structure uses steel, aluminium alloy and composite materials, which will be subject to atmospheric corrosion in the environment, including humidity, temperature, light, load (gravity load, wind load, snow load), and so forth. Pile components and grounding system will also be subject to soil corrosion. Whether embedded or embedded ground anchors, directly buried or concrete hammer heavy pile components shall be adopted.
(3) Corrosion of electric control system. From south to North and from west to East, China's climate is very different in different regions. The instrument panel and other electrical systems are also corroded and damaged. There are at least three climatic zones in China: high altitude zone, dry tropical zone and humid zone. Due to climate or corrosion, the corrosion rate and even corrosion mode of each area are different. For example, in high altitude areas, the mechanical properties of the instrument panel are reduced due to aging. In the dry and hot zone, the electrical performance decreases due to aging. In humid areas, high voltage induction PV modules are reduced.
(4) Molten salt corrosion of concentrated solar thermal power. China's centralised solar thermal power generation (CSP) began in the 1970s, and the annual power generation increased from 350 to 550 MW. Due to the use of different heat transfer fluids, such as nitrate, carbonate, chloride, and fluoride, their working temperature ranges are different, so the corrosion rates of various materials in the liquid are different. It is very important to understand the corrosion mechanism and characterise the corrosion rate of materials in molten salt. The influence of liquid impurities on molten salt corrosion is very useful for determining the standard of liquid composition. Finding a suitable mixture is also an important topic, because some mixtures have a relatively low corrosion rate, which makes the system have a long service life and low cost.
(5) Corrosion control techniques in solar energy. Various corrosion test and evaluation standards are established for solar PV modules, support structures and electrical control systems. Corrosion control technology has also been developed. Taking carbon steel, low alloy steel and alloy steel as examples, hot-dip galvanising and coating are selected to protect the steel structure. The hot-dip galvanised thickness of supporting parts, screw parts and offshore structures is defined, so that the supporting structures have a service life similar to that of solar PV modules. Similarly, salt spray requirements for steel, aluminium, and composite material (FRP) supporting structures are put forward to ensure service life and reduce construction cost. It is recommended to use appropriate gas inhibitors to protect electrical equipment from corrosion.

19.3 | Corrosion in wind energy in China

Over the past 12 years, wind energy has grown very rapidly in China. In 2020, China's wind energy accounted for about 50% of the world, and offshore wind energy accounted for about two-third of the world.

Corrosion has also become an important issue in wind energy, such as the corrosion of the monopole internals, grit connections, transition pieces, boat landing, J-tubes, towers, hub stairs, doors, main shaft bearings, gearboxes, brakes, control units, cooling and ventilation systems, equipment rooms and electrical equipment, and even blades. For example, the biological damage of boat landing is a big issue in China. In addition, in China's Bohai Bay and the Yellow Sea, freezing in winter also threatens the safety of wind blades and structures.

To improve the corrosion resistance of wind energy system, the new nanocomposite coatings with excellent performance were developed. The indoor acceleration test results indicate that the salt spray time is more than 5000h, seawater immersion 5000 h+, water condensation 2000 h+, UV aging 2000 h+, hydraulic oil resistance 8000 h+, and so forth. These excellent properties enable the coatings to ensure the service life of China's wind energy system of 30 years or even 50 years.

19.4 | Corrosion in nuclear in China

Over the past 8 years, China's nuclear power construction rate has been about six reactors a year, almost the same as that of the United States in the 1970s. At present, the total amount of nuclear energy ranks third in the world, second only to the United States and France. Since PWR is mainly used in China, corrosion is the most important problem threatening the safety and reliability of PWR. Since 2005, to ensure the safety and reliability of nuclear power plants, China has been investing a lot of research funds to understand the corrosion mechanism, develop test equipment, obtain corrosion data and develop life prediction methods.

For example, in situ scratch repassivation technology in high temperature and high pressure water has been developed to evaluate material corrosion, especially stress corrosion cracking (SCC). In other words, SCC can be defined by measuring the transient electrochemical parameters during scratch repassivation, which reduces the test time to 1/20 or 1/30 of the traditional test time.

The computer modelling for corrosion in nuclear power plants for various materials has also been conducted, including atomic scale ab initio, molecular dynamics simulation, micron scale cellular automata and millimetre or even metre scale finite element used in practical nuclear equipment. Daya Bay nuclear power plant also adopts the lifetime prediction method of nuclear components. The license extension for China's first commercial nuclear power plant was issued in 2020. In addition, HEA have been developed as potential nuclear materials. In recent years, the digital twinning methods are developing for nuclear power plants.

19.5 | Future challenges

Although many excellent research results have been obtained and applied to the real low-carbon energy industry, there are still many challenges, such as: (1) Corrosion mechanism understanding and control techniques development in various natural environments (atmosphere and soil); (2) molten salts corrosion and control techniques; (3) phase change energy storage materials: nitrates, chlorides, fluorides, liquid metals, and so forth—mixtures and less corrosive; (4) corrosion resistant materials including HEAs, and so forth, self-healing coatings, and inhibitors—'green' and environment friendly; (5) accelerated corrosion test method; (6) intelligent corrosion detection techniques; (7) lifetime prediction methods for component and system especially the digital twin method; (8) size effect: from first principle to digital twinning; (9) corrosion in geothermal energy and hydrogen energy.

20 | EXECUTIVE SUMMARY

A global transition towards more sustainable, affordable and reliable energy systems is being stimulated by the Paris Agreement and the United Nation's 2030 Agenda for Sustainable Development.[16,17] This poses a challenge for the corrosion industry, as building climate-resilient energy systems and infrastructures brings with it a long-term direction, so as a result the long-term behaviour of structural materials (mainly metals and alloys) becomes a major prospect.

With this in mind 'Corrosion Challenges Towards a Sustainable Society' presents a series of cases showing the importance of corrosion protection of metals and alloys in the development of energy production to further understand the science of corrosion, and bring the need for research and the consequences of corrosion into public and political focus. This includes emphasis on the limitation of GHG emissions, on the lifetime of infrastructures, implants, cultural heritage artefacts, and a variety of other topics.

In recent years, low carbon energy technologies have emerged as a strategic priority to reduce the global carbon footprint, decrease CO_2 emissions and improve air quality, so that is why this white paper begins with a focus on the importance of corrosion protection for the development and the reliability of renewables energies. This begins with a focus on solar (Chapter 2), geothermal (Chapter 3), and wind, waves and tidal energies (Chapter 4). Also featured are the 'green' and alternate sources of electricity production that lead to the development of energy storing systems like batteries and hydrogen technologies (Chapter 5), which also encounter materials and degradation issues.

Low carbon energies as proposed by the Intergovernmental Panel on Climate Change of the United Nations are also featured (Chapter 6), where the consequences of corrosion may have not only safety but public acceptance issues. Carbon capture, utilisation, and storage (Chapter 7) technologies mitigate CO_2 emissions, where the selection of materials is of key importance and where the corrosion knowledge and solutions coming from the traditional oil and gas production (Chapter 11) may be used. The changes in metal production processes (Chapter 8) to reduce the CO_2 production also influence the corrosion properties of alloys. For limiting the greenhouse emission, the transport industry (Chapter 9) reduces the weight of vehicles and airplanes with an important impact on the corrosion performance.

In addition, due to the changes in society and increased demands on power electronics resistant against climate stress (Chapter 10), corrosion research in the field of electronics and electrical engineering is taking an increasingly important role. Another important subject is infrastructure (Chapter 12) where the modelling of durability is a key issue, with an urgent need to investigate how the new binders used in coatings influence the durability of the structures. Additive manufacturing (Chapter 13) of metals is a very promising way for the elaboration of components if their corrosion properties are better understood. The durability of many components and structures exposed to (harsh) environments is based on a physical barrier, such as a coating, which would be able to protect much longer if it would have self-healing properties (Chapter 14).

And finally, the corrosion of metallic biomaterials (Chapter 15) in the human body and the preservation of metallic artefacts (Chapter 16) for our cultural heritage are two further areas which need to be taken care of. This white paper concludes with the importance of FEM and AI (Chapter 17) as tools to face the long-term degradation of metals and alloys and to also limit the pollution of the environment by metallic cations (Chapter 18).

To also address the efforts towards a sustainable industry in the fast growing market in China, the current developments are summarised in more detail in Chapter 19.

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Research data are not shared.

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REFERENCES

[1] International Energy Agency, World Energy Outlook 2020: Executive Summary, **2020**.
[2] U. Nürnberger, E. C. Köse, *Otto Graf J.* **2019**, *18*, 221.
[3] M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. A. Berger, K. Kato, T. Friesen, H. Liu, M. Van Iseghem, International Energy Agency Photovoltaic Power Systems Programme: Review of Failures of Photovoltaic Modules. Report IEA-PVPS T13-01:2014. **2014**. https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf
[4] Press release of the World Geothermal Congress 2020+1, Reykjavik.
[5] Battery Manifesto 2030, Horizon 2020 project Battery 2030+, www.battery2030.eu
[6] Hydrogen Europe, Horizon 2020 project Silver Frog.
[7] M. Lerides, European Project Horizon 2020 Alliance: Affordable Lightweight automobiles alliance, Accelerating the decarbonisation of transport, **2019**.
[8] www.worldautosteel.org
[9] S. Tjøtta, L. Dardinier, G. Rombach, R. Scharf-Bergmann, Recycling end of Life scrap into high quality extrusion ingot, Hydro, ET'2022: International Aluminium Extrusion Technology Conference, **2022**.
[10] J. O. Nilsson, Trace elements influence on filiform corrosion resistance in recycled 6060 aluminum alloys, EUROCORR, **2019**.
[11] https://modernairliners.com/airbus-a350-xwb-introduction/airbus-a350-xwb-specifications/
[12] https://modernairliners.com/boeing-787-dreamliner/boeing-787-dreamliner-specs/
[13] Alliance Project, Horizon 2020 (2016-2020).
[14] European Aluminium association, Eurocorr **2018**, Cracow.
[15] (a) Ricotta et al., (b) Gordon et al., (c) Tauber, (d) Ramirez Barat et al., in: Metal 2019, Proceedings of the Interim Meeting of the ICOM-CC Metals Working Group, Neuchâtel **2019**, eds. Chemello, Brambilla, Joseph, ICOM-CC.
[16] Transitions to low carbon electricity systems: Key economic and investment trends, IAEA, October **2019**.
[17] Transitions to low carbon electricity systems: Key economic and investment trends, IAEA, October **2019**.

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