



# ADVANCING SUSTAINABILITY IN CORROSION PROTECTION: ACRYLIC- BASED ECO-FRIENDLY COATING

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## ABSTRACT

The main objective of this review is to describe some of the important topics related to the use of preparation & characterisation of acrylic based anticorrosive eco-friendly coatings for electrodeposition purposes. In this context, “protective” refers to coatings for containers, offshore constructions, wind turbines, storage tanks, bridges, rail cars, and petrochemical plants while “marine” refers to coatings for ballast tanks, cargo holds and cargo tanks, decks, and engine rooms on ships. The review aims at providing a thorough picture of state-of-the-art in anticorrosive coatings systems.

**Keywords:** acrylic, anticorrosive, eco-friendly, coatings, electrodeposition

## I. INTRODUCTION

The annual costs related to corrosion and corrosion prevention has been estimated to constitute a significant part of the gross national product in the Western world. Although the value of such numbers is always debatable, corrosion issues are clearly of great importance in modern societies. In addition to the economic costs and technological delays, corrosion can lead to structural failures that have dramatic consequences for humans and the surrounding environment. Reports on the corrosion failures of bridges, buildings, aircrafts, automobiles, and gas pipelines are not unusual [2].

Throughout the last decades, both organic and inorganic coatings have been widely applied for the protection of metals against corrosion. In many areas of coatings technology, the fight against corrosion has made significant progress in recent years. For example development of new “corrosion resistant” alloys permits operation of critical processing equipment in highly corrosive environments over an ever wider range of conditions. However, despite significant improvements in coating technologies, problems continue in the long-term protection of metal from aggressive environments. Although the oil and pipeline industry has developed reliable cathodic protection methods and monitoring systems that permit safe operation in difficult environments, these industries also experience coating failures [2]. One of the main reasons for the limited number of high performance anticorrosive coating systems is the complexity of the coating-substrate system and the number of factors affecting the performance and service life of anticorrosive coatings. Besides the composition of the coating, which consists of binders, pigments, solvents, extenders, and additives, the performance and durability of anticorrosive coatings depends on several different parameters, such as type of substrate, pre-treatment of substrate, curing, coating thickness, adhesion between the coating and substrate, as well as several external environmental parameters. To perform its duty effectively, an

anticorrosive coating must possess intrinsic durability, adhesion to the substrate, adequate flexibility, and toughness to withstand impacts and cracking as well as maintain its appearance when subjected to stress, swell, mechanical abuse, or weathering [3].

The coatings industry is a mature industry that has been undergoing a continual change in technology throughout the last few decades. International and national legislation aimed at reducing the use of volatile organic compounds has led to significant changes in the formulation of anticorrosive coatings, which traditionally have contained a relatively large amount of organic solvents. The present trend of aiming to reduce emissions of VOCs will urge the coatings industry to develop products with high-solid contents, powder coatings, or waterborne coatings with low amounts of organic solvents. Although high-solid, inorganic, waterborne, and powder coatings are becoming more frequently applied, it may be difficult to substitute solvent-borne organic coatings completely in harsh environments [4].

An important aspect in the development of high performance coating systems for anticorrosive purposes in the marine and protective sector is a thorough knowledge and understanding of the interactions between the components in coatings. Furthermore, understanding of the fundamental physical and chemical mechanisms responsible for the failure of anticorrosive coatings during service may provide a basis for the design of novel new coatings. An example of premature coating failure on an offshore structure, leading to corrosion, is given in Figure 1.



Figure 1: Corrosion of steel on offshore structure due to premature failure of coating. Courtesy of Hempel A/S

In contrast to previous reviews that concern single (or a few) topics, the overall intention of this paper is to combine the main topics related to anticorrosive coatings technology [5]. The review, which is mostly based on European experience and practice, includes a description of the different types of environments anticorrosive coatings may encounter during service, an introduction to the different types of anticorrosive coatings presently available, the main components in anticorrosive coatings, novel anticorrosive coating ideas, and a summary of some of the most important degradation mechanisms [6].

## II. THE CORROSIVE ENVIRONMENT

Anticorrosive coatings are exposed to various environments ranging from constant immersion in water and burial in soil, to atmospheric pollution in industrial areas and ultraviolet radiation. The specific requirements for anticorrosive coating systems are naturally highly dependent on the environment and elements that the coating may experience during service, and the time of exposure. The versatility of the environments in which anticorrosive coatings are applied to protect metal against corrosion may be exemplified by the fact that coatings in industrial areas may be exposed to chemicals and rain, whereas coatings buried in soil may be exposed to bacteria and humidity [7].

## A. Classification of Environments

The versatility and different corrosivities of the environments that anticorrosive coatings may encounter during service necessitate some sort of classification of the different types of environments. ISO 12944 “Coatings and varnishes Corrosion protection of steel structures by protective coating systems” divides the environment into three types of exposure: immersion, atmospheric, and splash zone. The different types of exposure may be sub-classified as illustrated in Figure 2.

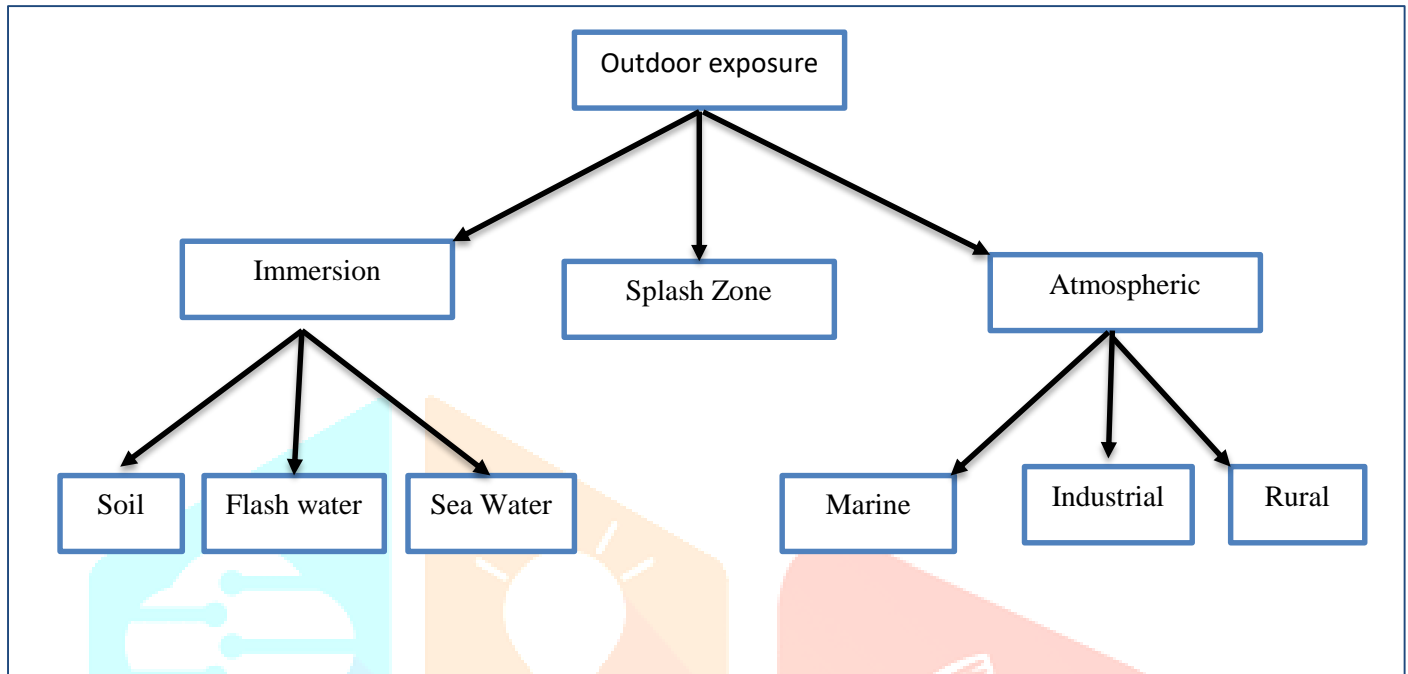


Figure 2: Classification of environments encountered by anticorrosive coatings

## B. Atmospheric Exposure

Coatings applied in atmospheric environments are subjected to locally alternating conditions with respect to ultraviolet radiation, heat, and moisture, as well as salt and gas concentrations. The corrosivity of the atmosphere can vary significantly depending on climate, level of pollution, and distance to the sea. The atmospheric environment may be classified according to six corrosivity categories ranging from very low (C1) to very high corrosivity (C5-I and C5-M), as illustrated in Table 1. Such categorizations will naturally be subject to debate because it is often difficult to specify corrosivity categories for one particular location (for example, roads may be heavily salted during the winter in rural areas where the location can, in principle, be categorized as both C3 and C5). However, they do provide a useful frame of reference for typical conditions encountered by coatings during service.

Table 1: Corrosivity categories and corresponding environmental impact factors

Corrosivity Class	Environmental Impact	Environmental Instances
C-1	Very Low	Relative humidity <60% for Indoor dry room condition.
C-2	Low	Ventilated room and Indoor in non-heated
C-3	Medium	High humidity in Indoor and high pollution. Rural environments industrial areas
C-4	Heavy	Industrial or urban areas
C 5-I	Very heavy industry	Very high relative humidity in industrial areas
C 5- M	Very dense marine	Offshore and coastal ranges

The corrosivity of rural environments is low compared to the corrosivity of industrial and marine atmospheres, which are categorized by a high or very high corrosivity. Industrial environments are characterized by a high content of solid particles in the atmosphere, particularly soot, sand, and sulphate salts. The combination of rain and a high content of sulphur dioxide in the atmosphere will result in acid rain and consequently expose the coating to an acidic environment. In comparison to industrial atmospheres, marine atmospheres are characterized by having a very high content of chloride ions, which are very aggressive towards metals and may cause pitting corrosion. Hence, marine and industrial environments with very heavy environmental impacts may provide very dissimilar conditions to anticorrosive systems. Therefore, they must be considered separately.

### C. Splash Zone

Structures situated near the waterline of the sea, such as parts of offshore plants and foundations of wind turbines, are located in a so-called “splash zone.” Splash zones are extremely aggressive environments because they combine an oxygen-rich atmosphere with continuous splashing of electrolytes from the sea. Hence, the corrosion process is not inhibited by a lack of oxygen or electrolyte solution. The degradation of coatings situated in the splash zone is likely to be accelerated further by exposure to ultraviolet radiation and the mechanical stress induced by continuous exposure to alternating periods of moisture and dryness.

### D. Immersion

In the case of structures immersed in water or buried in soil, the aggressiveness of the environment is very specific because the combination of temperature, salinity, pH, and the content of dissolved gases, especially oxygen, determines the overall corrosivity of the environment. Thus, it is difficult to indicate a specific corrosivity category of the environments. The following corrosivity categories may be applied for immersion in fresh water, sea water, and burial in soil, respectively: Im1, Im2, and Im3. The aggressiveness of soil on buried structures and coatings is mainly determined by the type of soil, humidity, bacteria, salt, and oxygen content, as well as pH. In comparison, the aggressiveness of a fresh water environment is mainly determined by the type and content of dissolved salts and oxygen. As opposed to fresh water, sea water has a high content of dissolved salts, especially sodium chloride, that are very aggressive towards metals and anticorrosive coatings. Structures immersed in water or buried in soil may also be affected by sand, gravel or stones. Structures immersed in water are also subjected to bio fouling.

## III. ANTICORROSIVE COATINGS

An anticorrosive coating system usually consists of multiple layers of different coatings with different properties and purposes. Depending on the required properties of the coating system, the individual coats can be metallic, inorganic, or organic. A typical anticorrosive system for highly corrosive marine environments usually consists of a primer, one or several intermediate coats, and a topcoat. The function of the primer is to protect the substrate from corrosion and ensure good adhesion to the substrate. For this reason, metallic zinc or inhibitive pigments are often formulated into coatings applied as primers for structures situated in the splash zone or in an atmospheric environment. The function of the intermediate coat is generally to build up the thickness of the coating system and impede transport of aggressive species to the substrate surface. The intermediate coat must also ensure good adhesion between the primer and the topcoat [8] [9]. The topcoat is exposed to the external environment and must provide the surface with the required color and gloss. In addition to adequate resistance to alternating weathering conditions and impacts from objects, the topcoat should also have a high resistance to ultraviolet radiation. The environmental degradation caused by moisture, temperature, and ultraviolet radiation will reduce the lifetime of the coating [10] [11].

The overall performance and durability of a coating system is very difficult to assess because it is affected by several internal and external factors. The complexity of the coating system and some of the variables that affect the performance and durability of an anticorrosive coating system are illustrated in Fig. 5. Many of the



factors, such as chemical, mechanical, and physical properties, as well as the chemical characteristics of the coating, can be manipulated by the formulators by their choice of binder system, pigmentation, solvents, and additives. However, it is also clear that several of the depicted factors, such as environmental properties, are outside the influence of the coating formulator. Consequently, any guarantee on anticorrosive performance and durability of a coating system must subsequently be based on “full-scale” (natural) exposure in combination with controlled accelerated laboratory tests with a specific coating and substrate.

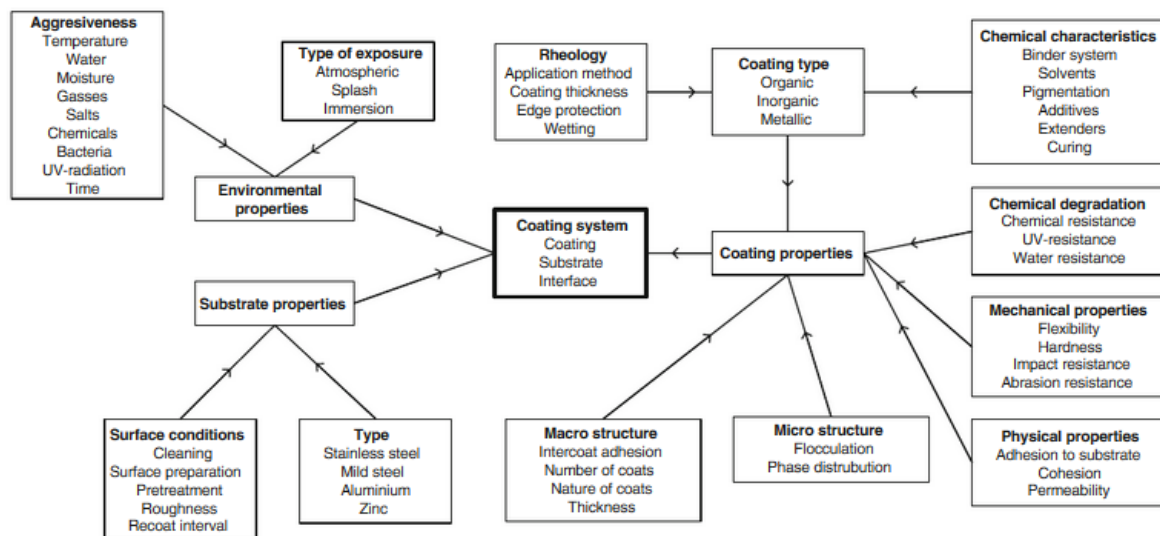


Figure 3: Factors affecting the durability of an anticorrosive coating system

In addition to the physical and chemical properties of the coating and the substrate surface, a coating system applied to a metal surface may contain inhomogeneities such as air bubbles, cracks, micro voids, contaminants, trapped solvents, non-bonded and weak areas, pigment-resins, and coating-substrate interfacial layers [12]. Each of these factors will influence the transport of aggressive species through the coating and along the coating-substrate interface (extending from a defect or damage in the coating) and subsequently affect the degradation process. The importance of avoiding defects in a coating is evident because non-defective anticorrosive coatings that primarily protect the substrate by obstructing the passage of water, oxygen, and cations may have lifetimes up to years. In comparison, the lifetime of coatings containing a physical damage will be much less. Consequently, the permeability of anticorrosive coatings to aggressive species is of great importance in the ability of a coating system to protect metals against corrosion. In a recent review focusing on the permeability of water and oxygen, several structural attributes of polymers in relation to the permeability of organic coatings to oxygen and water have been addressed [13].

The existence of internal stress in the coating, which develops due to an inability of the coating to shrink, may add further to the complexity of the coating system. Internal stress in coatings can significantly affect the durability of anticorrosive coatings by resulting in loss of adhesion, cracking, or cohesive failure. Some of the most important types of physical and aesthetic defects are described in coating textbooks on technology. Some textbooks also discuss the causes of the failure, and possible ways to avoid failures in anticorrosive coatings.

### A. Protective Mechanisms

Anticorrosive coatings are generally classified in accordance with the mechanisms by which they protect a metal against corrosion. Figure 4 illustrates the three basic protective mechanisms of anticorrosive coatings: barrier protection, passivation of the substrate surface (inhibitive effect), and sacrificial protection (galvanic effect).

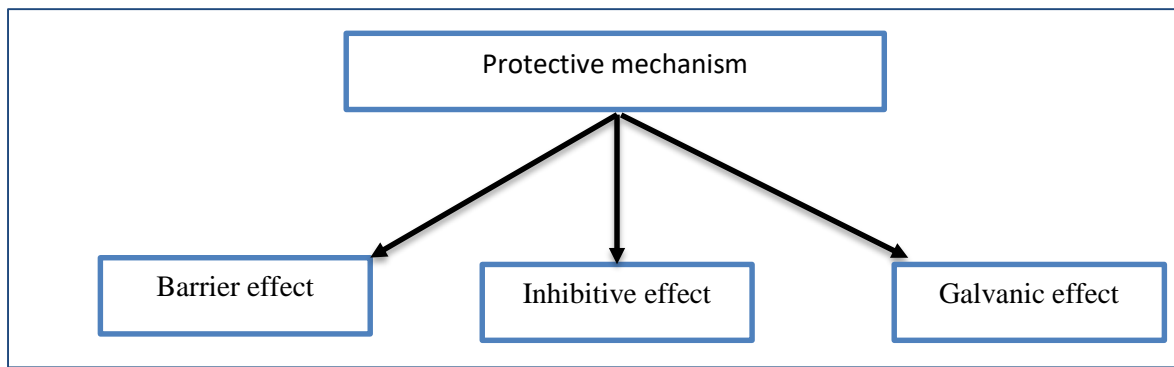


Figure 4: Protective mechanisms of anticorrosive coatings

Barrier protection is obtained by impeding the transport of aggressive species into the surface of the substrate by application of a coating system with low permeability for liquids, gases, and ions. Passivation of the substrate surface can be obtained by a chemical conversion layer, or by addition of inhibitive pigments to the coating. Metallic, organic, and inorganic coatings have all been widely applied for protection of metals against corrosion by means of sacrificial protection i.e., protection is obtained by sacrificial corrosion of an electrochemically more active metal, which is in electrical contact with the substrate. Although metallic anticorrosive coatings have been subjected to extensive research, they are considered to be outside the scope of this paper. Further information on metallic coatings may be found in some of the reviews on metallic coatings [14].

## B. Barrier Coatings

Barrier coatings may be used as primer, intermediate, or topcoat, and are often applied on immersed structures. Barrier coatings are typified by an inert pigmentation, typically titanium dioxide, micaceous iron oxide, or glass flakes, at lower pigment volume concentrations, but lamellar aluminum is also often applied. The lower pigment volume concentration results in dense and cohesive coatings with significantly lower permeability towards aggressive species than any of the other two types of coatings.

The degree of protection offered by a barrier coating system is highly dependent on the thickness of the coating system as well as the generic type and nature of the binder system. The delamination of both defect-free and artificially damaged barrier coatings has been reported to be significantly reduced when the thickness of the coating is increased because coatings behave as semipermeable membranes. In general, the anticorrosive performance of barrier systems increases when the same film thickness is built up from multiple successive thin coats rather than a single coat, but labor costs and potential revenue loss due to downtime push towards fewer and thicker coats.

The original assumption was that barrier coatings inhibit corrosion by acting as a barrier to water and oxygen from the environment. However, studies indicate that the mechanism of barrier protection relies on the ionic impermeability of the coatings. The ionic impermeability of barrier coatings ensures that moisture at the coating-substrate interface has a very high electrical resistance. Thus, the conductivity of the electrolyte solution at the substrate is so low that the transfer of corrosion current between the anode and cathode is minimized.

Cathodic protections may be used as a supplement to barrier coatings with immersed and buried systems to ensure satisfactory protection of the substrate in the case of damage to the coating system. The main principle of cathodic protection is to impress an external current to the material, which forces the electrode potential into the immune region.

The external current can be produced in two different ways:

- By means of a less noble material in the form of sacrificial anodes, which are connected by metallic conductors to the metallic structure?
- By means of an external current source, usually a rectifier. A reference electrode may be used to control the current from the rectifier.

### C. Sacrificial coatings

Sacrificial coatings rely on the principle of galvanic corrosion for the protection of metals against corrosion. This means that the substrate is protected by a metal or alloy that is electrochemically more active than the material to be protected. In this respect, coatings formulated with metallic zinc powder have been extensively employed for corrosion protection of steel structures for several decades. Unlike barrier coatings, sacrificial coatings are only applied as primers because they are only effective if the coating is in direct contact with the substrate due to the requirement of electrical contact between the substrate and the sacrificial metal. Furthermore, sacrificial coatings should only be applied with great care on structures submerged in water due to the subsequent permeation of water, which may cause the sacrificial metal to corrode.

In zinc-rich primers, zinc is used to produce an anodic ally active coating. Zinc will behave as an anode and sacrifice itself to protect the metal, which becomes a cathode. The resistance towards corrosion is dependent on the transfer of galvanic current by the zinc primer, but as long as the conductivity in the system is preserved, and as long as there is sufficient zinc to act as anode, the metal will be galvanic ally protected. The electrochemical activity in a damaged zinc coating system results in the formation of zinc corrosion products, which tend to seal the pores between the zinc particles to a point at which the system becomes electrically nonconductive, as illustrated in Figure 5. Subsequent protection is attributable to the barrier effect by corrosion products.

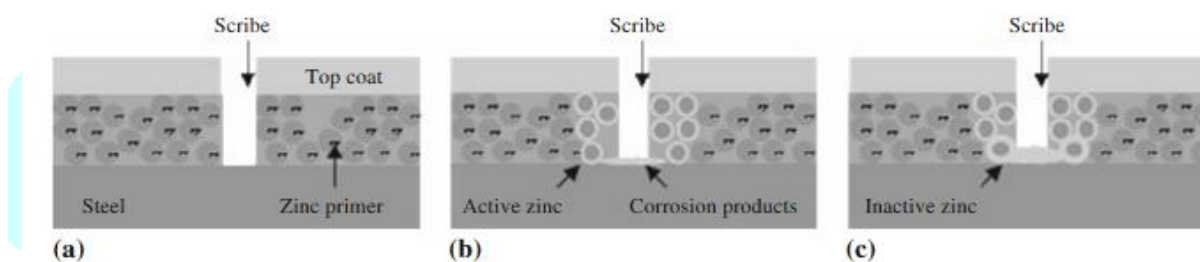


Figure 5: Stylistic sketch of the working mechanisms of a zinc-rich coating system. (Step a) Damage is introduced down to the steel surface. (Step b) Zinc around the score is still active while zinc-iron corrosion products are being built up. (Step c) The zinc is not galvanically active any longer but the coating provides barrier and inhibitive protection

The performance of sacrificial coatings is based on transfer of the galvanic current. This means there must be metallic contact between the individual particles of the sacrificial metal. Hence, sacrificial coatings usually are very highly pigmented, typically just below the critical pigment volume concentration. Indeed, the highest electrical conductivity is typically reached at a concentration of zinc particles in the range of 92–95 wt% of the dry film. 63,64 Since such a coating only contains 5–8 wt% of binders and very low amounts of other components for securing the mechanical properties, the adhesive and cohesive strength, as well as its resistance to impacts, is significantly reduced

### D. Inhibitive coatings

Inhibitive coatings are primarily applied as primers because they are solely effective if dissolved constituents can react with the metal. These coatings are mainly applied to substrates subject to environments with a risk of atmospheric corrosion, in particular industrial environments, and are generally not recommended for immersion in water or burial in soil.

The anticorrosive mechanism of inhibitive coatings relies on passivation of the substrate and build-up of a protective layer consisting of insoluble metallic complexes, which impede transport of aggressive species by acting as a barrier. The inhibitive pigments are inorganic salts, which are slightly water soluble. In Europe, phosphates are the most used cations. On a worldwide basis, however, chromates, molybdates, nitrates, borates, and silicates are also frequently used as cations in the inorganic salts. When the coating is permeated by moisture, the constituents of the pigments are partly dissolved and carried to the substrate surface. At the surface of the substrate, the dissolved ions react with the substrate and form a reaction

product that passivates the surface of substrate. This means that inhibitive pigments must be high enough to ensure sufficient leaching from the coating. However, if the solubility of the inhibiting pigments is too high, blistering can occur.

### **E. Inorganic coatings**

Inorganic coatings are made of natural compounds from the earth strata, such as quartz, minerals, and inorganic mineral colorants. Among the most widely applied inorganic coatings are zinc silicates. Zinc silicates are unusual coatings and are one of the few coatings that are pigmented above the critical pigment volume concentration. This means that not all of the solid pigment particles are covered with polymer, and all of the gaps between particles are not filled with polymer i.e., the coatings are designed to be porous. The high pigmentation of zinc silicates provides excellent protection against corrosion if the coating is applied as specified. However, the high level of pigmentation means that zinc silicates have a high risk of mud cracking. Mud cracking occurs as a result of internal stress that develops during curing if zinc silicates are applied too thick. Hence, the application of zinc silicate or zinc epoxies as primers in anticorrosive coating systems is subject to debate.

Another type of inorganic coatings is based on the sol-gel technique, which relies on dispersions of inorganic metal salts with solid particles. The sol-gel process technique of creating ZnO, SiO<sub>2</sub>, and SiO<sub>2</sub> – TiO<sub>2</sub> coatings for protection against metal corrosion has been extensively studied. The microcrystalline structure of inorganic coatings results in excellent aesthetic appearance, high abrasion resistance, and the lower absorption of UV-radiation with no significant loss of gloss or change of color. The inorganic particles in the sol-gel coatings generally provide an excellent barrier against aggressive species. However, it is difficult to apply sol-gel coatings in the thickness required for obtaining excellent anticorrosive properties without a risk of cracking. Furthermore, sol-gel coatings are brittle and use a high processing temperature not applied to large-scale structures.

In recent years, the desire to combine the properties of organic polymeric materials and inorganic ceramics has resulted in extensive research in hybrid organic-inorganic coatings for corrosion protection. The development of hybrid inorganic-organic materials using the sol-gel method allows incorporation of organic polymeric materials into an inorganic network. In addition to increasing the compatibility with most organic coating systems, the presence of polymeric materials increases the mechanical flexibility and toughness of the coating. The presence of inorganic materials may enhance the adhesion in comparison to a pure organic coating because certain inorganic components are capable of reacting with the metal surfaces. The incorporation of polymeric materials is also believed to reduce the porosity of the coating by sealing open pores between the inorganic particles, which subsequently improves barrier properties. The most widely applied hybrid inorganic-organic material is modified organosilanes (polysiloxanes), which are prepared by hydrolysis and condensation of organically modified silicates with traditional alkoxide precursors. The solution-based nature of the hybrid sol-gel coatings allows for the incorporation of water-soluble alkoxides. In present anticorrosive coating research, great attention is paid to the use of inorganic-organic hybrid sol-gel coatings modified with inorganic particles or extenders for replacement of pre-treatments such as phosphatizing.

## **IV. CHARACTERIZATION AND PROPERTIES**

### **A. Effect of Nano fillers on the Microstructure and Morphology of Coatings**

In case of organic matrices, the appropriated dispersion of the nano fillers is crucial to obtain final desired properties. The small size of the nano particles exhibits some advantages since it enables penetrating into ultra-small holes, indentation, and capillary areas in the polymer matrix. For example, the incorporation of nano particles into epoxy resins showed an enhancing of the integrity and durability of coatings thanks to the filling up of microcavities and cracks in the coatings [15] [16]. Nanoparticles can also prevent disaggregation of the polymer during curing, leading to a homogenous coating. In a recent study, it was



recognized that nanoparticles with a higher specific surface area not only exhibit an increase of the distribution of nanofillers in the epoxy matrix but also enhance epoxy-curing process [17] [18] [19]. For polyester coatings, Golgoon et al [20] reported that the embedding nanoclay created a denser coating and more uniform and less pores in comparison with the pure polyester coating. The presence of nanofiller can also perturb the crystallization of polymer. In many cases, nanofillers enhance the crystallinity degree and reduce the spherulites size of semi-crystalline polymers.

In the case of inorganic matrices, the formation of nanocomposite structures is connected with a segregation of the one phase to grain boundaries of the second phase, and this effect is responsible for stopping of the grain growth [21]. Li et al. [19] reported that the presence of nanoparticles (anatase and rutile nano-TiO<sub>2</sub>) reduced the grain size of the nickel matrix. For conventional materials, size of grain of monocrystals varies from about 100nm to several hundred millimetres. In this case, the number of atoms in grains is much greater than that in boundary regions. For nanocrystalline materials, the grain size is about 10nm or less [22]. By adding nanocrystal phase into the metal matrix, the volume fraction of grain boundaries might increase. Mitterer et al. [18] formed nitride nanocrystalline phases within a metal matrix, such as TiN in Ni [23], ZrN in Ni [24], ZrN in Cu [20], and Cr in Cu [18]. In these coatings, one metal may be converted into nitride in the nanocrystalline phase and the other may be transported into the growing film unreacted. On the other hand, thermal post treatment has strong effect not only on the grain size [16], crystallization [15], and morphology [18] but also on the dislocation density and the interactions between nanoparticles and the matrix [22] or the bonding of microstructural phases [13].

## B. Effect of Nanofillers on the Mechanical Properties of Coatings

**Tensile and Impact Properties:** In case of organic matrices, the incorporation of nanoparticles into the epoxy coating enhanced significantly the impact strength of the epoxy coating [4, 5]. The epoxy coating modified with TiO<sub>2</sub> nanoparticles showed the best enhanced impact strength of all the epoxy coatings. The distinct improvement in their stiffness may be ascribed to the following two mechanisms: (i) the nanoparticles occupy pinholes and voids in the thin film coating and reinforced interconnected matrix, causing a reduction of total free volume and an enhancement of the cross-linking density of the cured epoxy. As such, the cured nanocomposite coating has reduced chain segmental motions and improved stiffness. (ii) Nanoparticles may act to prevent epoxy disaggregation. By using the Nano indentation method for these epoxy Nano composites [23], it was found that modification with nanoparticles did not always enhance the stiffness of the epoxy coatings. The presence of nano-SiO<sub>2</sub> in epoxy coatings increased Young's modulus up to 20 times, whereas nanoclay and nano-Fe<sub>2</sub>O<sub>3</sub> modified samples showed ~30% and ~25% decrease, relative to the unmodified epoxy coating, respectively. It was realized that, based on Young's modulus of the nanocomposite coatings, its stiffness depended heavily upon the integrity and internal properties of the coating surface, as under mechanical stress the microvoids between the nanoparticles or between the polymer matrix and the nanoparticles may become the origin of cracks. Ragosta et al. [5] reported that the addition of nano-SiO<sub>2</sub> up to 10wt.% brought a significant enhancement in fracture toughness and an increase in the critical crack length for the onset of crack propagation. In the case of inorganic matrices, the presence of nanograins in the amorphous matrix improved the protection against impacts of high speed microparticles [2].

**Hardness:** For traditional organic and inorganic coatings, the measurement of microhardness can be used for evaluation of hardness. However, for the nanocomposite coatings, in order to study the effect of nanoparticles on the hardness of coatings, AFM based nanoindentation is found to be more appropriate [4], with the size of AFM tip being about 50nm. An extra result can be obtained from this nanoindentation is Young's modulus of coating [4].

## V. CONCLUSION

Meeting environmental regulations and reducing production costs remain a key challenge and a major driving force for new developments in anticorrosive coatings. The challenge to coating suppliers is to find a solution with a more environmentally friendly profile, without sacrificing the proven performance features of the traditional formulations. This challenge is more severe for the protective coatings sector than for less-demanding segments of the coatings market, which explains the lower penetration of new technologies such as water-borne coatings in the protective segment to date. The next generation of high-performance anticorrosive coatings faces many challenges, and the incomplete understanding of the physical and chemical mechanisms responsible for the failure of anticorrosive coatings during service needs to be clarified.

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