

Characterization of corrosion scale productson coated Cor-ten steel when exposed to the atmospheric and fully immersed condition

Submitted in partial fulfilment of the requirements for the award of Bachelor of
Engineering degree in Mechanical Engineering

BY

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**DEPARTMENT OF MECHANICAL ENGINEERING
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SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of Adithya H (38150004), Thejua Krishna B C (38150119) who carried out the project entitled **"CHARACTERIZATION OF CORROSION SCALE PRODUCTS ON COATED CORTEN STEEL WHEN EXPOSED TO ATMOSPHERIC AND FULLY IMMERSED CONDITION"** under our supervision from September 2021 to April 2022.

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DECLARATION

I Aditya H (38150004), Thejua Krishna B C (38150119) hereby declare that the Project Report entitled **“CHARACTERIZATION OF CORROSION SCALE PRODUCTS ON COATED CORTEN STEEL WHEN EXPOSED TO ATMOSPHERIC AND FULLY IMMERSSED CONDITION”** done by me under the guidance of Dr J R Deepak and is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Mechanical Engineering.

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PLACE: Chennai

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ABSTRACT

Cor-ten A588 steel are a kind of weather resistant steel i.e., the steel has corrosion resistance properties and coatings like Cu Ni Cr can be used to enhance these properties. But some of the drawbacks of Cor-ten A588 steel are they are vulnerable against chlorides, de-icing salts and various industrial pollutants like Sulfur dioxide. Cor-ten A588 steel have many applications such as outdoor structures like bridges, sculptures and various marine, industrial infrastructures.

In order to counter the drawbacks of Cor-ten A588 steel, we are conducting various corrosion tests to analyze and characterize the corrosion resistance properties of Cor-ten A588 steel and find a solution to enhance these properties. For our research paper, artificial corrosion tests like salt spray test and Immersion test are conducted to determine the corrosion rate of coated and uncoated Cor-ten A588 steel. The coating of the Cor-ten A588 steel with Cu, Cr, Ni is done by electroplating technique. Then, the surface morphology and elemental composition are done with the help of SEM/FESEM and XPS. In continuous immersion for 1-2 weeks rusts formed on the immersed uncoated Cor-ten A588 steel show two separate layers one layer of loose layer and the other one adherent greasy type of rust inside.

In the powder substance, the amount of O is high while, in the coated raw amount of C is higher than O this only means that the Ni Cu Cr (tri-layer) coating prevents much more than the normal Cor-ten A588 steel. Also, the weight loss analysis is performed on coated and uncoated samples with 3.5% NaCl for two weeks and the results exhibit minimum weight loss in Cr, Cu, Ni coated Cor-ten A588 steel samples. Hence, the study reveals that the Cu, Cr, Ni coated Corten A588 samples is the perfect candidate for various construction, marine and industrial applications.

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LIST OF ABBREVIATION

USSC	–	UNITED STATES STEEL CORPORATION
ASTM	–	AMERICAN SOCIETY FOR TESTING MATERIALS
HSLA	–	HIGH STRENGTH LOW ALLOY
Mm	-	MILLIMETRE
Mpa	-	MEGAPASCAL
SO ₂	–	SULPHUR DIOXIDE
XRF	–	X-RAY FLUORESCENCE
α	–	ALPHA
β	–	BETA
γ	-	GAMMA
Cu	–	COPPER
Cr	–	CHROMIUM
Ni	–	NICKEL
C	–	CARBON
O	–	OXYGEN
SiC	-	SILICON CARBIDE
WEDM	–	WIRE EDM
SEM	–	SCANNING ELECTRON MICROSCOPE
XPS	–	XRAY PHOTOELECTRON SPECTROSCOPY
TEM	–	TRANSMISSION ELECTRON MICROSCOPE
SE	-	SECONDARY ELECTRONS
BSE	–	BLACK SCATTERED ELECTRON
FEG	–	FIELD EMISSION GUN
HVAC-R	–	HEATING VENTILATION AIR CONDITIONING AND REFRIGERATION

CHAPTER 1

INTRODUCTION

1.1 COR-TEN A588 STEEL

As early as the nineteenth century, there was interest in developing corrosion-resistant steel. In the 1930s, the US Steel Corporation began developing low-alloy steels containing copper, nickel, chromium, silicon, and phosphorus. As a result, the USSC has given these steels the trade name Core-Ten, which stands for Corrosion-Resistant Tensile Strength. [Wiss Janney 2013] In the early 1940s, the American Society for Testing and Materials (ASTM) was also exploring improved corrosion-resistant low-alloy steels, mainly developing its first weather-resistant steel, A242. [McDad et al. 2000] Corten A588 is used in the Bridges, walls, roofs, and towers, as well as a variety of architectural uses

Most metals that are exposed to seawater are damaged due to the phenomenon known as corrosion, for metals that are used for engineering purposes, seawater is the most corrosive naturally occurring electrolyte the most important factors that determine seawater corrosion are environmental and biological, the zone and rate of exposure. Mild steel has low corrosion resistance for vast environmental conditions and it leads to the formation of rust and some loss of mechanical properties, the Corrosion rate can be reduced, but it cannot be completely prevented because the process of corrosion is spontaneous phenomenon. The corrosion of a particular metal or material can be fast or slow, depending on the environmental conditions. For example, the famous Delhi Iron pillar in India was made almost 2000 years ago and is almost as good as, it should be considered that it has been exposed to arid environmental conditions. Attempting to reduce corrosion is very important for better industrial production, public safety measures, and avoiding various dangerous health hazards. Cor-ten A588 steels have low-alloy, high-strength steels with excellent corrosion resistance.

There is an increased interest in metallic coatings on Cor-ten A588 steel surfaces to keep the steel's cathodic protection. surface. Corrosion of weathering steel can generally be divided into 3 distinct phases: initial rapid corrosion, decreasing corrosion rate and protective layer formation and finally, a phase that is stabilized with linear loss of corrosion. Cor-ten A588 Grade steel is a copper, chromium, nickel, phosphorous, and silicon-based high-strength low-alloy steel (HSLA). The addition of phosphorus and silicon to the Cor-ten A588 Grade steel improves its corrosion resistance.



Fig. 1.1: Photograph of Cor-ten A588 steel plate (source www.indiamart.com/proddetail/corten-a-steel-15395208848.html)

After continuous exposure to corrosive atmospheres, an embedded protective oxide layer (patina) forms on Cor-ten A588 steels, which protects Cor-ten A588 steels from corrosion. Kira et al. The chromium-rich coating increases corrosion resistance and is easy to handle in both wet and dry situations; as a result, the uses of A588 Corten steel can be expanded in different grades. It's worth noting that a protective oxide layer is normally produced after the coating is applied. 1 to 3 years of atmospheric exposure to A588 Corten steel (depending on environmental conditions). The main difference between A588 stainless steel and carbon steel is that this patina essentially acts as a protective layer for the steel, reducing the rate of corrosion of A588 Cor-ten steel. Even though cadmium (Cd) plating has a better corrosion resistance rate, cadmium's carcinogenic nature has an impact. To increase the mechanics and corrosion resistance of Cor-ten A588, it is necessary to produce ecologically safe metallic coatings such as copper, chromium, and nickel. The primary steel corrosion materials and oxidation end products under various conditions were inferred based on the environment of the samples, and the complicated conversion ratio between distinct corrosion products was estimated.

1.2 PROPERTIES OF COR-TEN A588 STEEL

1.2.1 Chemical compositions of Cor-ten A588 steel

The chemical composition of Cor-ten A588 steel (grade 1 and grade 2) with a thickness of 0.8 mm to 50 microns, a width of 750 mm to 1500millimetersr and a length of upto 1200millimetres is given below.

Table 1.1: Chemical components of Cor-ten A588 steel

Composition	Grade A	Grade B
Carbon	0.150	0.150
Manganese	0.549	0.499-1.00
Phosphorus	0.06-0.160	0.04
Sulphur	0.060	0.050
Silicon	0.100	-
Copper	0.20-0.60	0.290-0.099
Chromium	0.24-1.31	-
Nickel	0.20-0.70	0.40-1.999
Molybdenum	-	0.999

1.2.2 Physical properties of Cor-ten A588 steel

Physical properties are discussed here, such as modulus of elasticity, coefficient of heat capacity of thermal expansion, thermal conductivity, and electrical resistance of Cor-ten A588 steel.

Table 1.2: Physical Properties of Cor-ten A588 steel

Weathering resistant steel	Standard		Tensile strength Mpa		Yield Strength Mpa		Elongation (min)%	
ASTM A588	ASTM		484		344		21	
Elastic modulus (unit: N/mm2)								
Cor-ten A588 steel					193~20.69*10 ⁴			
NAW 490					20.49*10 ⁴			
Coefficient of Thermal expansion (unit *10 ⁻⁶ /°C)								
Temperature range (From room temp)	Up to 100°C	Up to 200°C	Up to 300°C	Up to 400°C	Up to 500°C	Up to 600°C		
Corten A588 steel	10.49	11.79	12.79	13.40	13.49	13.60		
Thermal Conductivity								
Temperature (°C)		Cal/cm sec°C			Kcal/m Hr°C			
100		1.33*10 ⁻¹			47.2			
200		1.17*10 ⁻¹			42.4			
300		1.04*10 ⁻¹			37.7			
400		0.93*10 ⁻¹			33.7			
500		0.85*10 ⁻¹			30.9			
600		0.80*10 ⁻¹			27.8			
Electrical Resistance								
Temperature °C	20	100	200	300	400	500	600	
Resistivity	20.3	23.8	29.4	38.5	50.3	63.5	79.2	

From the above table, we can identify the physical properties of Corten A588 steel.

1.2.3 Mechanical properties of Cor-ten A588 steels

Cor-ten A588 steel has better weather resistance properties. However, due to the use of P as an alloying element, the toughness of this steel grade is lower than that of Cor-ten B. Cor-ten A steel is ideal for sheet steel structures that aren't prone to brittle fracture.

Table 1.3: Mechanical Properties of Cor-ten A588 Steel

Steel grade	Thickness	Mechanical properties		
		Yield strength	Tensile strength	Elongation
	mm	Newton/sq mm	Newton/sq mm	% Minimum
Cor-ten A	2-13	345	485	20
Cor-ten B	2-60	345	485	19

The preceding table lists the mechanical characteristics of Cor-ten A588 steels. The mechanical characteristics of steel are determined by the kind of steel processing (hot or cold rolling). Cold-rolled Corten steel sheets are easier to cold-form but have slightly different mechanical properties. A typical minimum elongation for cold-rolled sheet steel is 25%.

1.2.4 Corrosion resistance properties of Cor-ten A588 steel

Corrosion resistance - this alloy consists of copper, nickel and a large amount of phosphorus. These metals add some anti-corrosion properties. When these plates are exposed to the atmosphere, the copper fuses with the steel, forming a protective layer that is easy to protect against corrosion.

Weather resistance - When the Cor-ten A588 steel plate is exposed to the atmosphere, a layer known as patina forms on its surface. The layer of patina thus formed resists weathering while keeping the underlying surface intact. When compared to standard carbon steel, Cor-ten A588 steel has a higher resistance to air

corrosion. In situations of continuous humidity, on the other hand, Because the patina does not stable under circumstances of persistent humidity or underground, the corrosion rate of Corten A588 can be as high as carbon steel. If chlorides are rinsed off routinely in maritime conditions, stable oxide layers on steel can develop. Through the use of unpainted Corten A588 for salt fog/spray applications is not advised in general.

1.2.5 Applications of Cor-ten A588 steel

Weather-resistant or Cor-ten steel is widely used for outdoor steel buildings because it is superior to ordinary carbon steel in outdoor conditions. This eliminates the need for regular repainting of the steel. Two examples are the design of buildings and bridges. A protective rust coating reduces the rate of corrosion to the point that by the time the level of corrosion becomes dangerous, the structure has already outlived its design life for other reasons. Bridges made of weather-resistant steel offer great advantages in terms of lifetime costs.

Cor-ten A588 steel is the material of choice for several outdoor projects. Outdoor sculptures must be one of the most common uses; this is because Corten Steel can quickly build up a layer of rust to protect the sculpture and give it a weathered effect. For this, not only Corten steel plates are used, but also some bridges and other structures. Cor-ten steel plates are used for smaller projects including home gardens. When a concrete wall doesn't fit and will overwhelm the rest of your garden, an alternative is often chosen.



Fig. 1.2: An application of Corten steel bridge (source <https://usbridge.com/>)

There are several items with Corten steel; including bike hoops, tree trellises and planters for bushes and shrubs. After all, we believe that public space may be both functional and beautiful.

It is very widely used in shipping, in the construction of intermodal containers, and also invisible sheet piles. It is widely used in railway cars, containers, bridges and other fields such as construction, engineering equipment, coal mining equipment and other large equipment exposed to the atmosphere and special working conditions.

Corrosion resistance: As we all know, many bridges are designed close to the surface of the water, and some even bridges over the sea, whether it is seawater or river water, in some cases will be affected by tidal events that flood the bridge deck. This has higher requirements for bridge materials. If ordinary steel is used, rust will soon appear. Corrosion phenomena and the use of Corten steel products in bridge construction can effectively reduce these corrosion phenomena, making the bridge-building more durable.

Beauty: Corten steel products naturally corrode after being used for a certain period. The colour of this corrosion can change over time. This coloured element has been added to the design of many buildings for heavy effect. Corten steel products are used in bridge construction, which imperceptibly increases the thickness of the bridge.

Longer service life: Corten steel products, after corrosion, form a dense oxide film on their surface, which tightly seals the base and external corrosive substances to protect the base material from corrosion. This feature can increase the life of bridges.

1.2.6 Drawbacks of Cor-ten A588 steel

In such situations, weather-resistant steel cannot be used because its corrosion resistance is insufficient to withstand such conditions. Weather-resistant steel cannot be used in areas with high chlorine content, so the protective anti-corrosion coating will not be able to withstand high levels of corrosion current. As a result, the system will fail sooner rather than later. Weather-resistant steel should not be used in

applications that may result in galvanic corrosion or corrosion caused by extreme pH levels

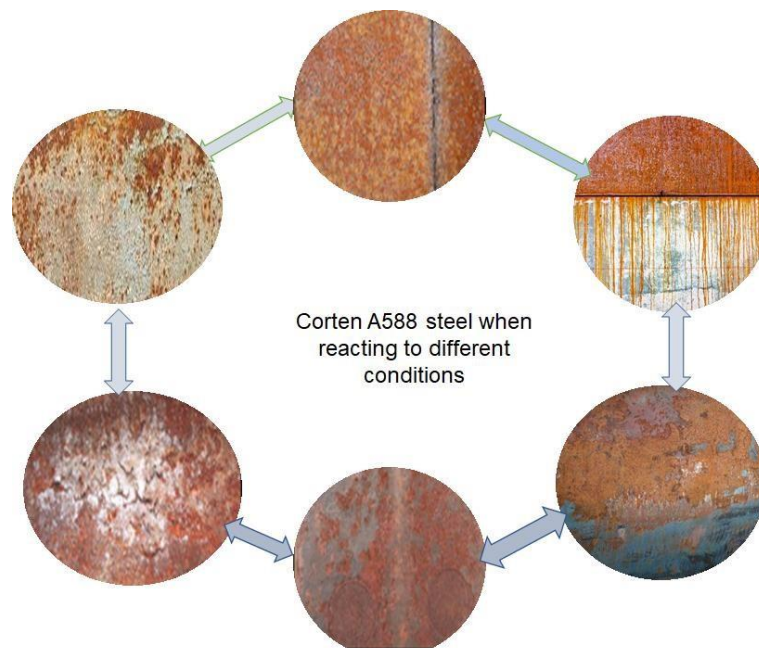


Fig. 1.3: Effects of Chlorides, De-icing salts, Pollutants, Drainage and Staining on Cor-ten A588 steel

Disadvantages of weatherproof steel plate: you need to fight against rust, and the pattern colour variety is more delicate, there are more problems with it. Many treatments are not cheap. It is suitable for large buildings, medium and small buildings, and the finest buildings. While weather-resistant steel may seem ideal, there are several factors to consider before starting construction. Certain weather and climate conditions can lead to durability and corrosion resistance issues. For example, weather-resistant steel should not be built in a high chlorine environment.

Also, it works best with alternate wet and dry cycles. If the environment is constantly wet or humid, such as submerged in water or buried in the ground, this reduces the steel's ability to resist corrosion effectively. While many appreciate the aesthetics of its natural rusty patina, it also creates the possibility of staining nearby structures; therefore, it is best to keep it away from concrete or other easily distorted materials.

1.2.6.1 Effects of Chlorides on Cor-ten A588 steel

A coastal environment with a considerable volume of airborne sea salt particles is an environment where a protective coating of rust cannot form spontaneously on weather-resistant steel



Fig. 1.4: Images of Cor-ten A588 steel when exposed to chloride (source <https://distressedmetals.com/corten/limitations/>)

Areas within a mile of the ocean that are continually exposed to salt spray are included in the oxide layer. When salt is repeatedly accumulated on a steel surface, the rust product akageneite is formed., which is a non-adherent rust product that is not conducive to the creation of a protective oxide layer on the inside surface in high concentrations Items manufactured of weather-resistant steel that use a lot of chlorides (salt) as a rust film starter should be avoided. They will eventually show their oxide layer's non-adhesive nature, failing to provide adequate corrosion protection, which is frequently required when using weather-resistant steel as a cladding material.

1.2.6.2 Effects of De-icing Salt on Cor-ten A588 steel

De-icing salts used on highways near weather-resistant steel might pose problems in extreme conditions. As long as steady and concentrated amounts are not accumulated on the surface of the weathering steel, which cannot be washed away by rain, their use is generally not a concern.

1.2.6.3 Effects of Pollutants on Cor-ten A588 steel

Avoid places where there are a lot of harsh chemicals or industrial pollutants like Sulphur dioxide (SO₂). Today, high Sulphur dioxide settings are uncommon, and investigations show that having industrial environments with normal to low concentrations of pollutants aid in the layer formed oxide layer on the steel. Up to two-thirds of steel production already involves refining, and large amounts of carbon dioxide are emitted when coal and coke are burned as part of the process. This can be hazardous to human health and may cause environmental problems.

1.2.6.4 Effects of Drainage / Retention Traps on Cor-ten A588 steel

Protective oxides do not crystallize in constant damp or humid circumstances, especially when water "drains" or gathers in pockets retaining traps. Corrosion rates will be faster and colours will be brighter in these regions that cannot dry completely. Wet trash and dense vegetation growing around the steel can also aid in the long-term retention of surface moisture. Keep moisture and dirt out of the steel members and make sure they're well aired.

1.2.6.5 Effects of Bleeding / Staining Traps on Cor-ten A588 steel

Exposed weathering steel's first surface weathering (rust flash) generally results in extensive rust stains on neighbouring surfaces, particularly concrete.



Fig. 1.5: Bleeding/staining of Cor-ten A588 steel (source <https://distressedmetals.com/corten/limitations/>)

Avoiding designs that discharge loose rust products over neighbouring surfaces or pre-treating the metal before installation will help to limit staining.

1.3 ELECTROPLATING PROCESS

Electroplating is the process of migrating metal ions from a positive electrode to a negative one in a solution. An electric current passing through the solution causes the material at the cathode to become coated in the solution.

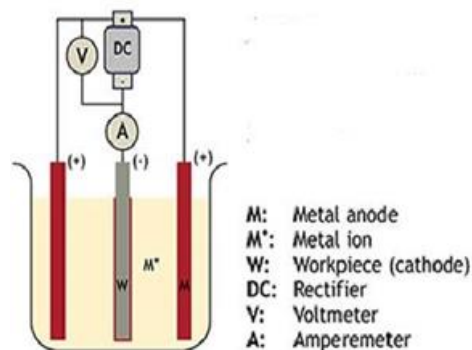


Fig. 1.6: Electroplating Makes Use of an Electrical Current

(source : <https://interplex.com/electroplating-guide>)

1.3.1 Copper Plating

Copper plating is attractive but also resistant to corrosion and wear. Depending on the organic additives, the overlay can have hardness values from 150 to 500 HV. The metal layer may have different levels of internal stress and ductility. Bright nickel looks yellowish in daylight and tarnishes easily; for this reason, it is usually plated with a top coat such as chrome or gold.

Copper sheets are very decorative and have good electrical conductivity. Depending on the additives, the severity can vary from 90 HV to 200 HV. For functional applications, one copper layer is often overlaid with another metal layer.

1.3.1.1 Benefits of copper plating

- Copper sheets have excellent thermal and electrical conductivity.
- Extensive properties can be obtained by changing the investment conditions
- Many metals and plastics are easily coated with copper.
- Copper plating is an important step in the production of printed circuit boards.

1.3.1.2 Restrictions of copper plating

- Copper may stain in the air or on contact; This requires a metallic or organic topcoat.

1.3.1.3 Applications of copper plating

- A copper coating can be applied to components and parts like premium threaded connections, couplers, tubulars, risers, and alloy premium bore pipes. Copper is also immensely beneficial as an undercoating for those other plated metals in high-corrosion environments to improve rust resistance.

1.3.2 Nickel Plating

Nickel layers are not only attractive, but also resistant to corrosion and wear. Depending on the organic additives, the overlay can have hardness values from 150 to 500 HV. The metal layer may have different levels of internal stress and ductility. Bright nickel looks yellowish in daylight and tarnishes easily; for this reason, it is usually plated with a top coat such as chrome or gold.

1.3.2.1 Benefits of Nickel plating

- Attractive decorative layer
- Corrosion and wear-resistant

- Different compositions of baths can be used for a variety of purposes.
- It can be used on a range of different substrates.
- Good undercoat for other surface finishes.

1.3.2.2 Restrictions of Nickel plating

- Discoloration of nickel in the air requires the use of a topcoat; electronics may need a final layer of gold
- Nickel may cause allergic skin reactions.

1.3.2.3 Applications of Nickel plating

Hard disc drives for computers are the most common application, but other examples include metallizing plastic products for electroplating, vehicle brake cylinders, pumps, valves, and other engineering products. Electroless nickel plating seamlessly integrates wear and corrosion resistance with outstanding adherence to all metals.

1.3.3 Chromium Plating

Chrome plating (or chromium plating, as it is more commonly known) is the process of electroplating a light coating of chromium upon a metal object. Chrome is the end result of chrome plating. The chrome plated layer can be visually pleasing, corrosion resistant, make cleaning easier, or increases the surface hardness.

1.3.3.1 Benefits of Chromium plating

A chrome-plated finish is the best protection against wear and corrosion on a machine. Despite high-friction environments, a chromium metal finish prolongs the life of your parts. Chrome plating protects against corrosion in environments where other base materials are prone to corrosion. Chromium has a gleaming appearance, does not corrode, and is scratch resistant.

1.3.3.2 Restrictions of Chromium plating

- Chromium plating is an expensive process.
- Since it is a non-uniform coating, it must be overplated.
- Seeing as chromium is indeed a carcinogenic substance, it is extremely toxic.
- Lead anodes have been used in chromium plating, resulting in toxic lead waste.

1.3.3.3 Applications of Chromium plating

- Hydraulic cylinders and pistons.
- Automotive and mechanical components.
- Rolls, molds, dies, screws and other forming surfaces.
- Press punches and tooling.
- Mining and agriculture equipment.
- Shafts and rotors for pump applications.
- Components used in textiles and printing.

1.3.4 Inspection

Finished products are electroplated and subjected to a series of tests to ensure good coating quality. Typically, these tests may include:

Adhesion: twist, fold, bake and/or tape.

Appearance: visual and microscopic (up to the level of magnification agreed in the contract)

Possibility of soldering

Adhesion: eg. ultrasonic wire connection

Porosity: may include nitric acid vapor or immersion, electrolytic or gas methods.

Thickness: X-ray fluorescence (XRF) or microsection.

CHAPTER 2

LITERATURE SURVEY

Following are the categories which have been studied for this research, it has been categorized into 4 sections

- i. FESEM/SEM AND EDAX on Cor-ten A588 steel
- ii. XPS on Cor-ten A588 steel
- iii. Immersion test on Cor-ten A588 steel
- iv. Salt spray test on Cor-ten A588 steel

2.1 SEM/FESEM AND EDAX ON COR-TEN A588 STEEL

Yang Guo et.al (2020) In his research on Raman and XPS depth profiling to examine the corrosion rate of Fe-Si-Al alloy in a salt spray environment, he discovered that Scanning electron microscope processing shows different oxide layers with frilly surfaces from which he discovered that the decrease in oxide content is due to an increase in depth. We are seeing similar results in our research as well.

Jiawei Yang et al (2016) In their scientific work on the Impact of Cr on the Behavior of Rust Film Formed on Low Alloy Steels, immersed in a 3.5 per cent NaCl solution, researchers discovered that the concentration of Cr is higher in the inner rust layer developed on Corten steel, which favors amorphization. The production of α -FeOOH with a tiny crystalline structure doping Cr is caused by an increase in Cr concentration in the rust layer. The fine structure of α -FeOOH may help to improve the rust layer's compactness. Yamashita discovered the significance of Cr in the structure of α -FeOOH by studying Cr-goethite, which also showed cation selectivity. The findings demonstrated that a high concentration of Cr in the rust layer causes the establishment of a protective inner rust layer. We have also encountered a similar situation during our investigation.

Q.C. Zhang et.al (2002), finds Cu retards the expansion of the rust, suppresses the flow of oxygen to the steel surface, Cu diminishes the conductivity of the rust, precipitates and encloses the steel surface, retards the crystal growth of rust, and adds to a uniform dissolution of the steel and the forming of a rust layer at the early phase, according to his study on Corrosion behavior of weathering steel in marine atmosphere. he also discovered that Cr may be soluble in Fe to create a solid-liquid with high solubility, despite the fact that Cr content in oxide molecule is limited. Because of the differing solubilities in rust and steel, the element Cr of the steel must be redistributed when a weathered steel substrate is transformed into oxides. Some Cr replaces Fe in iron oxyhydroxide to create $\alpha\text{-Fe}_x\text{Cr}_{1-x}\text{OOH}$, and some Cr precipitates on flaws and grain boundaries, as we've seen in our corrosion research.

Mindaugas Daukšys et.al (2019) In his investigation of the impact of Sodium chloride and Sodium silicate solutions on the visual aspect of weathering steel when the ambient temperature varies cyclically, he discovered that the corroded surfaces appear bright red, yellow, clay loam, black, or carbon black in appearance, implying that the corrosion products mainly contain lepidocrocite, goethite and magnetite. The rust of samples stored in a 3 per cent Sodium chloride solution contained the maximum amount of iron ions, according to EDS analysis. The crystal structure of goethite and lepidocrocite was discovered by SEM examination. Lepidocrocite crystals have a floral plate structure, while goethite crystals have got cotton ball form. This rust moving mechanism is similar to crystallization. In the course of air corrosion, lepidocrocite is the initial material to crystallize. This mineral is red in color. Goethite can be yellow, sand-colored, or brown in color. We've seen a similar type of result for our investigation with magnetite, which is black or carbon black in color.

Zhifen Wang et.al (2013) discovered that Cr, Cu, and P, which improve the densification and adherence of the rust films, resulting in better corrosion control, in his scientific research on Observation of the rate of corrosion of weathering steels in atmospheric environments. Another way is to reduce the carbon content of steels in order to improve corrosion resistance of the steel. The effect of C content on property of corrosion should also be examined. Steel with a decreased carbon content has the potential to minimize strain energy and the percentage of Fe_3C generated, hence improving corrosion resistance. When opposed to CS, the lower carbon content of WS helps to boost corrosion resistance. We also discovered

comparable outcomes.

Diaz et.al (2013) In his investigation on Corrosive environments of Ni-advanced weathering steels in oceanic atmospheres of mild salinity, he discovered that as the chloride ion deposition rate goes from 30 to 75 mg/kg(m² d), virtually doubles. The favourable effect of nickel in advanced weathering steels is readily apparent; as the amount of nickel in the steel composition increases, corrosion decreases. Specifically, regardless of atmospheric salinity, corrosion of developed weathering steel A3 (3 percent Ni) was approximately 20% lesser than conventional weathering steel.. In the marine atmosphere with the least atmospheric salinity (18 mg Cl/m² d), Ni-advanced WS is adherent and also has a silky finish without chipping, whereas rust molecules established on the very same WS in the coastal environments with 42 and 103 mg Cl/m² d atmospheric salinity had poor adhesion, great roughness, and obvious flaking, ruling out the need for uncoated 3 percent Ni-advanced WS. In our research, we discovered 16 different types of Ni characteristics.

J R Deepak et.al (2019) The features of Cu Cr and Ni were discovered in his study work on Mechanical and corrosion behavior of Cu, Cr, Ni, and Zn plating on Cor-ten A588 steel providing potential for improvement in ambient building applications. The dazzling ornamental layer of copper electrodeposited Cor-ten A588 steel demonstrates a homogeneous distribution over the substrate. A bright shining decorative layer of chromium plated Corten A588 grade steel Micro picture of Cor-ten A588 grade steel plated with Ni generated a consistently spreaded soft layer of Ni The top layer has a high concentration of copper, with levels of oxygen and iron, whereas the substrate has a high concentration of iron, with trace of other metals such as Si, Cr, Mn, and Ni. which is also responsible for corrosion resistance we also have similar types of results

Yuhai Qian et.al (2013), The positive effects of alloyed Cr is credited to both its advancement of the creation of a protective rust surface, which serves as a shield against corrosive environment, and its improvement of passivation abilities, which reduces the anodic dissolution of substrate alloys, according to his survey on Affect of alloyed chromium on the earth's atmosphere resistance to corrosion of weathering steels. With increasing Cr concentration, the peak intensity of lepidocrocite dropped. When the Cr content is increased, a considerably narrower corrosion product film forms, but it still has the microstructure of goethite. The diffusion technique was used to regulate the inactive current density of alloys having less than 9 wt% Cr, as well as the porosity of the passive layer reduced as the Cr concentration rises. The weight percentage of crystal goethite to all other ferrous oxides determines the protection against corrosion of weathering steels. When the weight ratio is greater than one, the resistance to air corrosion improves. The production of crystalline goethite was aided by the addition of Cr, resulting in a higher weight fraction of crystalline goethite to all the other ferrous oxides, implying increased air corrosion resistance. We discovered a similar form of analysis.

T. Kamimura et.al (2016) In his research of the composition and defensive capacity of rust layers formed on weathering steel exposed to a wide variety of environments, he discovered that the alloying Cu and Cr are enhanced in the rust surface, particularly in the inner rust layer, and that this enhances the rust surface's high protective ability.

Yueming Fan et.al(2021) In his study on the effect of chloride ions on corrosion protection of Ni-advanced Cor-ten steel in a modeled tropical coastal environment, he discovered that the effect of Cl on corrosion protection was proportional to Cl concentration. With the suppression of Cl, the corrosion resistance decreased. In a high Cl environment, the change from lepidocrocite to goethite was limited. Instead of being evenly distributed throughout the product film, Ni was contained primarily in the inner film. The inhibition of chloride ions on the formation of NiFe_2O_4 was steadily intensified as the chloride ion concentration grew, and the corrosion behavior of steel was diminished.

R.E. Melchers et.al (2008) The percentage of oxygen supply is generally considered the rate-limiting process inside the electrolytic corrosion process, and the focus is to minimize the permeability of the rusts to oxygen supply, according to his research paper A new explanation of the corrosion loss methods for weathering steels in oceanic atmospheres. Reduced rates of active chlorides, as well as certain air contaminants reaching the corroding surface, are also likely to be beneficial. We got the same results as well.

Sei J. Oha et.al (1999) He discovered that differing levels of nickel had no effect on the development of iron oxides in his research on Corrosive environments of varying steels in coastal, rural, and commercial environments. Ferrites produced on the surface of certain steels may not prevent further corrosion activities from causing steel loss. A outer coating, with its highly compressed tiny iron oxide particles, was earlier proposed to prevent oxygen and water from entering the steel substrate. The weathering steel's corrosion rate is decreased when an outer coating is completely formed. A protective layer was observed in the inner layer of the corrosion products. As a result, it's possible that now the innermost layer served as a protective shield, slowing down the corrosion rate. By thickly compacting the incredibly tiny particles, lowering the average particle size of the goethite might improve the protective surface's function in preventing oxygen and water penetration to the steel substrate. This recommended that the granules tried to prevent the protective layer from fully forming, leading to a higher corrosion rate of steel. Throughout the analysis, similar outcomes were seen.

Dhaiveegan Periyathambi et.al (2016) The great corrosion behavior of weathering steel is linked to the production of a deep and adherent rust coating, according to his research on Weathering Steel an Industrial Marine Urban Environment Research Project. The goethite phase distribution inside the innermost rust film was consistent, and thus served as a rust protective film. The production of permanent goethite inside the upward outer rust surface inhibits chloride ion access further into the upward inner layer, resulting in a less pronounced akageneite peak. The upward surface has a lower chloride concentration than that of the earthward layer. The concentration of chloride has an impact on crack development. The same results were discovered by us as well.

Renato Altobelli Antunes et.al (2003) Three zones of various colours (yellow, black, & red) were observed over the steel coupons in his scientific research on Identification of Corrosion Compounds Generated on Steels in the Initial Months of Environmental Exposure. For the growth and enhancement of substances corrosion resistance, chemical analysis of the oxide layer produced on metals and awareness of the its formation mechanisms were critical. Goethite resembles cylindrical structures are known as cotton balls (goethite), which are linked by structures that resemble nests or even crystalline goethite. The magnetite appears as black, flat areas. Lepidocrocite was the most common stage on weathering steel, following by goethite & magnetite. The morphological features discovered are similar to those observed in lepidocrocite and goethite (sandy crystals and floral structures) (cotton balls). The same kinds of outcomes were discovered.

2.2 XPS ON COR-TEN A588 STEEL

In his study on Aqueous Corrosion Behavior of Weathering Steel and Carbon Steel in Acid-Chloride Environments, Y.-S. Choi et al. (2000) discovered that x-ray photoelectron spectroscopic analysis (XPS) analyses revealed that the rust layer created in acid-chloride solution was made up of hematite (Fe_2O_3) and magnetite (Fe_3O_4). The weight loss method was used to calculate the rate of corrosion of weathering steels. In the Absorption spectra, there's some chromium oxide (Cr_2O_3) and cupric oxide (CuO) in the weathering steel's rust layer. This means that in an aqueous environment, such compounds encourage somewhat barrier protection rust layers on Cor-ten A588 steel. Similar types of spectra were discovered.

Yang Guo et al. (2020) discovered Raman and XPS depth profiling to investigate the corrosion behavior of FeSiAl alloy in a salt spray environment in his research on Raman and XPS depth profiling. A broad survey spectrum was obtained first in order to determine the surface components of Fe, Si, Al, O, C, and Cl after-corroded surface of FSA are affirmed as Fe, O, C. However, no XPS spikes for Al, Si, or Cl elements were found. It means that the amount of the Fe element is dominant in each layer, indicating that the surface layer is mostly made up of Fe-based matter. The concentration levels of C and O elements slowly decrease as sputtering time increases, whereas the concentration of Fe element increases. This is because the

depth has increased, the oxide content has decreased, and the substrate has been exposed. Furthermore, it can be clearly seen that the atomic content for Al, Si, and Cl elements remains nearly constant with sputtering time. Similar kinds of components were discovered in our results as well.

Q.X. Li et al. (2008) discovered that IR spectra were used to analyse the composition of the powered rust in his study on Characterization of the rust formed on weathering steel exposed to Qinghai salt lake atmosphere. The primary absorb peaks were identified using the reported iron oxide spectra. The main rust compositions on the both surfaces were β -FeOOH and γ -FeOOH. Amorphous α -FeOOH was discovered, and elements found in the rust layer were obtained. Both field-ward and skyward rust layers contained the foreign elements O, Mg, Al, Si, Cl, K, and Ca. And their components in the rust of the skyward surface were lesser than those in the rust of the fieldward surface. In the salt lake atmosphere, Cl has a significant impact on the corrosion of Cor-ten A588 steel.

J R Deepak et al. (2019) discovered elements such as Si, Cr, Mn, Cu, and C in his research work on Mechanical and corrosion behavior of Cu, Cr, Ni, and Zn electroplating on Cor-ten A588 steel for scope for improvement in ambient construction applications. The range of elements present in the nickel film electroplated on Corten A588 grade steel shows a tight layer of chromium and chromium oxides like CrO, Cr₂O, and FeOOH on the top layer, which is responsible for increasing corrosion resistance. A nickel, nickel oxide NiO, and Ni(OH)₂ [3] passive top layer. The coated steel has an elegant smooth layer of nickel with 98.02 percent nickel content, as well as trace amounts of iron in the substrate. The iron content was determined to be 97.80 percent.

2.3 IMMERSION TEST ON COR-TEN A588 STEEL

RAMAN et al. (1989) discovered in their scientific study Morphological traits of Created Rust Stages on Cor-ten A588 Steels in Lab Corrosion Tests that the rust forms as a slurry deposit on the steel surface, later sedimenting into 2 separate layers of loose and adhesive rusts in the continuous, fully immersive test. It starts out as clusters of an amorphous form with a cotton ball exterior, some which later converts to α -FeOOH. During the later stages, only a tough outer, single layer of rust

was acquired, and this rust surface demonstrated better adhesion to the steel surface. At the top of this tough outer, uniform, and compact rust layer, researchers discovered clusters of bent plates of crystalline γ -FeOOH, as well as some δ -FeOOH and α -FeOOH

In his research paper Resistance To corrosion of High-Efficiency Weathering Steel for Bridge Construction Applications, Ai hue Chen et al. (2012) discovered that after 72 hours of cyclic immersion accelerated corrosion testing, the inner rust layer on HPS was made up of α -FeOOH phase and denser than that on PCS, which was a mixture of α -FeOOH and α -Fe₃O₄. HPS rust provides better protection, and HPS corrodes at a lower rate than PCS. Copper and chromium enrich the layer of rust in HPS and improve the rust layer's compactness The roles of Cu and Cr against corrosion are discussed depending on the outcomes of the rapid immersion corrosion tests and rust layer analysis, and we are also getting similar results.

Resistance to corrosion of Cor-ten A588 steel – a review paper by V.K. Bupesh Raja et al. (2020). According to a review, the corrosion resistance of weathering steel is closely related to the chromium content. The addition of chromium significantly reduced corrosion of the weathered steel. The rate of corrosion of the experimental steel after 96 hours of immersion was 1.101 g.m⁻².h⁻¹. The rust of weathering steel was primarily composed of the FeOOH and Fe₃O₄ phases, with the development of α -FeOOH aided by the ascent of chromium material. Based on these findings and ours, we can conclude that chromium plays a role in the resistance to corrosion of Cor-ten A588 steel.

N.K Tiwary et al. (2016) discovered that the immersion corrosion test in 3.5 percent NaCl shows that the rate of corrosion of steel A increases significantly, while the same for steel B decreases with time in their research study because of mechanical properties and microstructure characterization and corrosion outcomes of old railway girder bridge steel and modern weathering steel structures. High oxygen concentrations facilitate the creation of oxide, hydroxide, and oxy-hydroxide during corrosion tests in NaCl solutions. Cr is a powerful oxide film forming essential component that is less soluble in the internal rust layer than Fe oxide, reducing the formation of additional corrosion products. A similar phenomenon was observed during our research as well.

2.4 SALT SPRAY ON COR-TEN A588 STEEL

Renato Altobelli Antunes et al. (2014) discovered in his academic research on Characterization of Corrosion Products on Carbon Steel Exposed to Natural Weathering and to Accelerated Corrosion Tests that accelerated corrosion tests, such as salt spray, are of great interest for a variety of industries due to their ability to provide results faster than natural weathering. Another type of iron oxyhydroxide, akageneite (β -FeOOH), is commonly found in chloride-containing environments. It was possible to link the hue of the oxide to a specific phase. The red oxide observed was found to be typical of lepidocrocite γ (-FeOOH). The yellow areas are a combination of lepidocrocite and goethite. The formation of magnetite can occur from the inner to the outer rust layers, as the transformation of lepidocrocite into magnetite is favored when the oxygen supply is low.

In his research paper on the corrosion and fatigue performance of weathering steel and High-Performance steel for bridges, Yu Zhang et al (2020) discovered that in a salt spray environment, a rust layer quickly develops on the surfaces of all the specimens of type A, after which the rust layer becomes thicker and more compact. A brown and rough rust layer covers all of the corroded specimens. Furthermore, the formation of a rust layer results in an obvious volume expansion of specimens, and our study found a similar result.

CHAPTER 3

AIM AND SCOPE OF THE PROJECT

3.1 AIM

- The kind and features of the rust that occurs on the surface of steel have been proven to be significant since they define the steel's protective properties. Indeed, the rust layer features have been linked to the differential in corrosion resistance in Cor-ten A588 steel.
- It's critical to thoroughly investigate the corrosion resistance of the rust ingredients through surface morphology analysis SEM and elemental compound analysis XPS.
- This investigation should encompass not only the identification of the constituents but also their meticulous characterization.

3.2 SCOPE OF THE PROJECT

- The outcome of the project will be a detailed report, presented in the journal with the characteristic properties of Cor-ten A588 steel and the properties of coated Cor-ten A588 steel.
- This report consists of the different corrosion nature of Coated Cor-ten A588 steel and Cor-ten A588 steel.
- The microstructural and the elemental analysis of the Corten A588 and Coated A588 steel determines the properties of the corrosion by products produced due to the 3.5% NaCl solution and also their stability in nature and uses

3.3 PROBLEM DEFINITION

Cor-ten A588 steel are kind of steels which belongs to low alloy higher strength type of steels. They are weather resistant steel and are used for various industrial and marine infrastructural applications, for example bridges and shipyard

constructions, however when they are exposed to severe corrosive environments, they do undergo corrosion. Some of the key factors leading to these drawbacks are the exposure of Cor-ten A588 steel to chlorides, de-icing salts and pollutants like sulfur dioxide. Sulfur dioxide can be hazardous to human health and may cause environmental problems.



Fig. 3.1: Cor-ten A588 steel when reacts to various pollutants

Drainage/retention and bleeding/staining of the Cor-ten A588 are some of the phenomenon that catalyzes and leads to the faster corrosion rate of Cor-ten A588 steel. Protective oxides do not crystallize in constant damp or humid circumstances. Avoiding designs that discharge loose rust products over neighbouring surfaces or pre-treating the metal before installation will help to limit staining.

CHAPTER 4

METHODOLOGY

4.1 METHODOLOGY IN RESEARCH WORK

In this research work we are conducting various test and analysis to characterize metallurgical and the corrosive properties of coated and uncoated Cor-ten A588 steel. A graphical representation of the procedures has been given in flow chart below

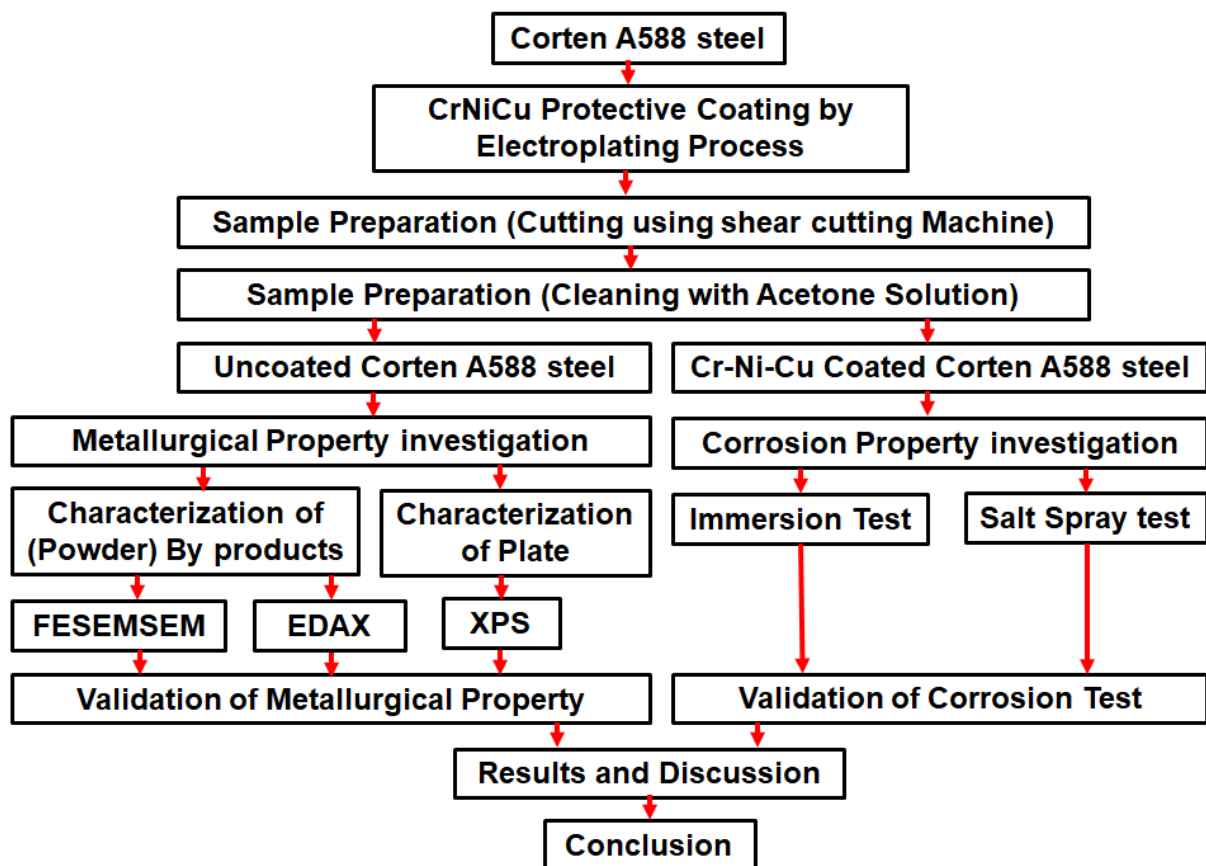


Fig. 4.1 Flow chart about the process in the research work

4.2 WORKFLOW PROCESS IN COR-TEN A588 STEEL

The first step in the preparation of coated Cor-ten A588 steel is the electroplating of the Tri-layer coating of Ni, Cu and Cr on Corten steel using the electroplating

method. After the preparation, both the Coated and the uncoated Cor-ten A588 steel undergo immersion and salt spray tests. Then the prepared specimen after 14 days is used to study the surface morphology and elemental analysis of Cor-ten A588 steel after corrosion.

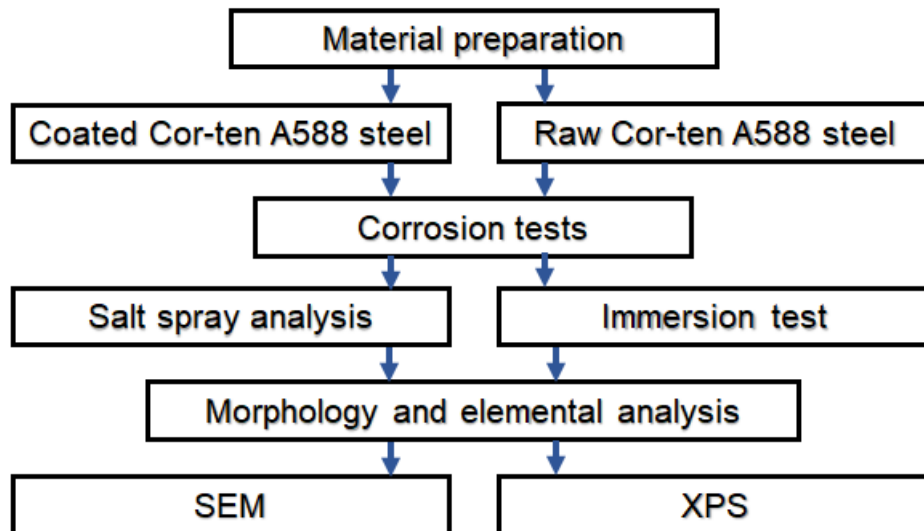


Fig. 4.2 Flow chart of Work flow process

CHAPTER 5

EXPERIMENTAL WORK

It is done in Sharif's Forging at Chennai, Tamil Nadu and supplies 3millimetre thick Cor-ten A588 steel. The sample is first chopped into 150*75*3millimetre dimensions using WEDM (Wire Discharge Machine). On a polishing machine, the material is then shined with various grades of silicon carbide sandpaper. Finally, colloidal slurry silica is utilized to produce mirror-like polished material, which are then washed with acetone to eliminate waste particles. A tabletop optical emission spectrometer is used to verify the chemical composition of the substance to confirm its quality. According to ASTM B734, B688, and B650, Corten A588 is electroplated with chrome-copper nickel and degreased with HCl before being washed with water.

5.1 ELECTROPLATING ON COR-TEN A588 STEEL

Cor-ten A588 steel is used as the substrate cathode and coated metals (Cu, Cr, Ni) as the anode rod. For Copper plating, CuCl is used to make the copper bath, and CrO₃ and NiSO₄(H₂O)₆ are being used as raw materials to make the electroplating bath solution for the plating process. The factors used to electroplate Cu-Cr-Ni in Cor-ten A588 steel are shown in Table below.

Table 5.1: Factors in electroplating of Cu Cr Ni on Corten steel A588 grade

Compounds	Temperature (K)	Voltage (Voltage)	Current (ampere)	Duration (minutes)	Coating Thickness (Micrometer)
Copper alloy	333-343	3	11	60	10.18±0.07
Chromium alloy	329-333	6	151	30	4.60±0.05
Nickel alloy	383-343	5	101	60	18.06±0.16

The coated samples were passivated in nitric acid for 30 minutes after electroplating with copper, chromium, and nickel on Cor-ten A588 steel. The samples were then washed in hot water and dried thoroughly. The metal was cut into dimensions of 15*10*3 millimeter using WEDM after the electroplating Cu-Cr-Ni on steel Cor-ten A588 (wire EDM). XPS (X-ray photoelectron spectroscopy) is used to assess the coating's crystal structure, and then SEM is used to examine the cross-section of the coated sample.

By completely submerging galvanized test specimens in water, the corrosion tendency of the test specimens was investigated. and untreated Cor-ten A588 steel in the form of specimens measuring 15*10*3 mm in a 3.5% NaCl solution. The sample was purified in accordance with ASTM G1-04 (2010). Immersion tests are carried out on samples of steel grade Corten A588 with dimensions of 20 * 10 * 3, cut on a WEDM machine, a hole with a diameter of 2 millimeters is drilled to completely immerse the sample in order to suspend it in 150 milliliters of 3.5percent sodium chloride solution in the cylindrical flask.

The weight of the materials is measured on a physical condition before diving. Before and after immersion, record the electrical conductivity & pH of the metal. For around two weeks, the entire plant is maintained at room temperature. The weight loss technique is used to figure out the corrosion rate in this procedure. Coated and uncoated specimens were exposed to salt spray for 250 hours for the salt spray test. For 250 hours within the cabinet, a 3.5 percent NaCl solution is sprayed on both samples.

After salt spray and dip testing, surface morphology and elemental composition analysis is determined by XPS and SEM.

5.2 SCANNING ELECTRON MICROSCOPE(SEM)

Mac-Mullen gave an overview of electron microscopy scanning's early beginnings. Although Max Knoll used a cathode beam scanner to picture a 50-millimeter field width demonstrating channel contrast in 1936, it was Man-fred Don Arden who pioneered the high-resolution microscope through scanning.

A very comparatively tiny raster that finely concentrates and reduces the beam of electrons. Arden employed electron beam scanning to get over the transmission electron microscope's (TEM) resolution limitations as well as the chromatic aberration issues that came with the initial TEM imaging. The numerous detecting modes, SEM capabilities, theory, and the first high-resolution SEM production were then described. The Zwoorkin Group reported on more operations in the mid-1950s, followed by the Cambridge groups developed by Charles Ottley, which led to the selling of the Cambridge Scientific mechanic Company's first commercial device, the "stereo scan." It was delivered to DuPont in 1965.

5.2.1 Samples preparation for Scanning electron microscopy

SEM specimens must be small enough to fit in the sample phase, and special preparations may be recommended to improve their electrical conductivity & stability so that they can withstand high vacuum and high-energy e-beam conditions. With a conductive adhesive, samples are generally connected tightly to a specimen holder .

SEM is commonly used for flaw inspection of semiconductor wafers, and manufacturers make equipment that can check each part of a 300 millimeter semiconductor wafer. Many gadgets have chambers that allow an item of that size to be spun continuously 360 degrees while at a 45-degree angle.

5.2.2 Principles and capacities

The signals used by SEM to make images are the result of an electron beam reacting with atoms at various depths within a specimen. Secondary electrons (SE), reflected or backscattered electrons (BSE), distinctive characteristics such as X-rays and light (cathodoluminescence), absorbed current (specimen current), and transmitted

electrons make up many sorts of signals. Secondary electron detectors are basic equipment in all SEMs, but detectors for all other conceivable signals are uncommon.

Secondary electrons have less energy of about 50 eV, limiting their average free path in solids. As a result, Secondary Electrons can only escape a few nanometers above a sample's surface. The signal from the secondary electrons is highly localized at the impact point of the primary electron beam, allowing images of sample surfaces with resolutions of less than 1 nm to be collected. Backscattered electrons are beam electrons that are reflected by an elastic scattering from a substrate sample, the reason is that they have high energy than Secondary Electrons, they emerge from deeper locations within the model, resulting in a lower resolution of BSE images than Secondary Electrons images. However, because the intensity of the BSE signal is strongly related to the model's atomic number (Z), BSE is frequently used in analytical SEM with spectroscopy from the characteristic X-rays. BSE images can only provide information about the distribution of the sample's components, not their identities. BSE imaging can show colloidal gold immune labels with diameters of 5 or 10 nanometers in samples containing light elements, such as the biological space maker, otherwise, Secondary electron images would be difficult, if not impossible, to detect. When an inner shell removes an electron from an electron beam sample, the X-rays emit characteristics that fill the high-energy electron shell and emit energy.

These characteristic features, such as X-ray energy or wavelength Energy-dispersing X-ray spectroscopy or wavelength-distribution X-ray spectroscopy can be used to identify and measure the abundance of elements in a sample, as well as map their distribution.

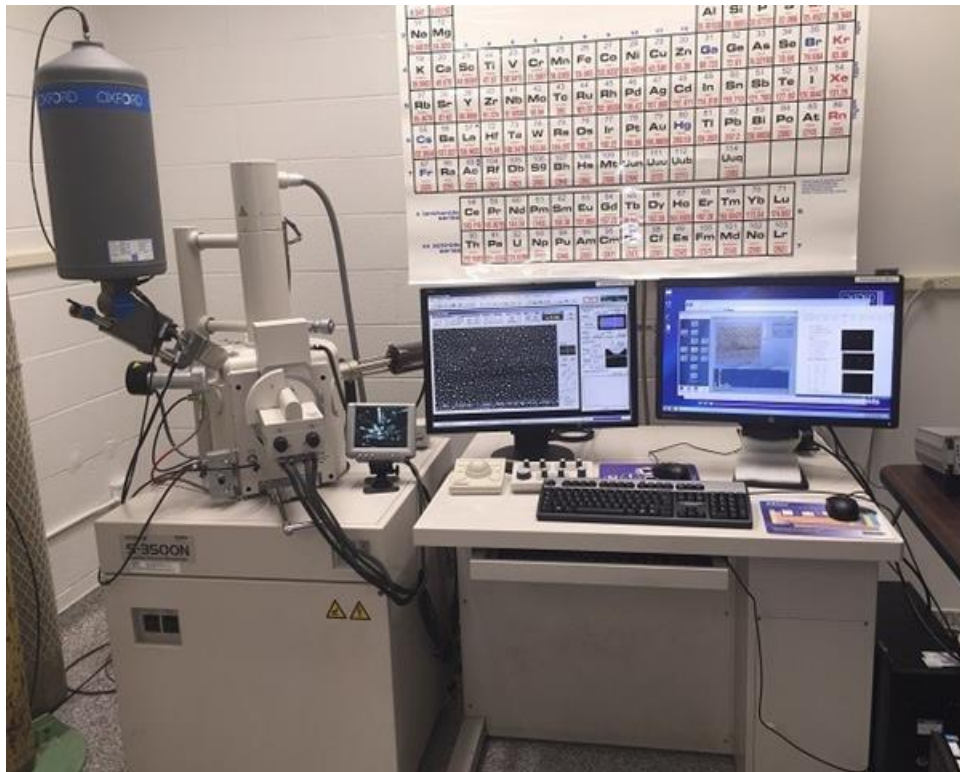


Fig. 5.1: Photograph of scanning electron microscope
(source <https://nicks.ksu.edu/equipment/sem.html>)

5.2.3 Scanning process and image formation

In a typical SEM, an electron beam is emitted thermionically from an electron gun attached to a tungsten filament cathode. Tungsten is widely employed in thermionic electron guns due to its high melting point and low vapor pressure, Its ability to be heated electrically for electron emission, as well as its low cost, make it appealing. Lanthanum hexaboride cathodes are another type of electron emitter, as is upgrading the vacuum system to use a standard tungsten filament SEM or Field Emission Gun (FEG), tungsten single crystal emitters or cold-eyed cathode, and thermally assisted Schottky type emitters coated in zirconium oxide.

5.3 X-RAY PHOTOELECTRON SPECTROSCOPY(XPS) ON A588 COR-TEN STEEL

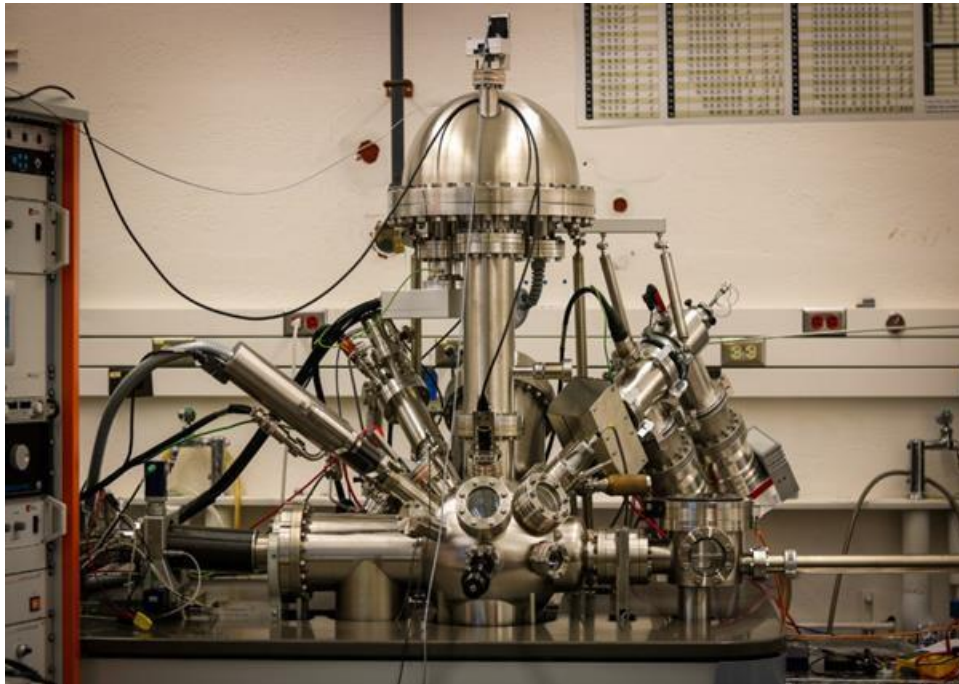
X-ray photoelectron spectroscopy (XPS) is a photoelectric surface-sensitive quantitative spectroscopic technique that can identify the elements that exist in a

material (elementary structure) as well as its chemical composition. The density of electronic states in a material and its general electronic structure. XPS is a powerful measurement method because it displays not only the existing components but also the other components to which they are related. This technology can be used for both linear profiling of elementary structures across the entire surface and depth profiling in conjunction with ion beam etching. It is frequently used to investigate chemical reactions in materials after they have been formed or fissured, scraped, heated, exposed to ultraviolet light, or during ion implantation.

XPS is a photoemission spectroscope that determines the electron population spectrum by irradiating an object with an X-ray beam, and the chemical conditions are determined by measuring kinetic energy and the number of ejected electrons. XPS requires high vacuum (residual gas pressure $p < 10^{-6}$ Pa) or ultra-high vacuum ($p < 10^{-7}$ Pa) conditions; however, XPS at atmospheric pressure is currently being developed, in which samples are analyzed at a single pressure. A few tens of millibars.

XPS detects all elements except hydrogen and helium when using laboratory x-ray sources. The detection limit is in the thousandths of a millimeter, but parts per million (ppm) can be achieved with longer collection times and top surface concentrations.

Inorganic compounds, alloys, semiconductors, polymers, elements, catalysts, glass, ceramics, paints, paper, inks, wood, plant parts, cosmetics, teeth, bones, medical implants, and biomaterials are all commonly analyzed using XPS. Coatings, viscose oils, adhesives, ion-modified materials, and other products are available. XPS is frequently used to analyses hydrated forms of materials such as hydrogels and biological samples prior to analysis, to be frozen in an ultrapure environment under hydration conditions and to scan several layers of ice.



***Fig. 5.2: Photograph of x-ray photoelectron spectroscope
(source <https://www.ccmr.cornell.edu/instruments/x-ray-photoelectron-spectroscopy-xps/>)***

Because the energy of an X-ray of a specific wavelength is known (Al K X-rays, $E_{\text{photon}} = 1486.7 \text{ eV}$) and measures the kinetic energy of the emitted electrons, the electron binding energy of each electron can be calculated using the photoelectric equation.

The measured electron's binding energy (BE) in comparison to the chemical potential is binding, the photon's energy is the energy of the X-ray photons employed, and the measured electron's kinetic energy is the kinetic activity. It requires a modest correction to the device's working function since it has contact potential in the actual dimensions, as with the word for the specific surface of the material. This equation is essentially the protection of the energy equation..

Work function can be thought of as an adjustable device correction factor that causes some eV kinetic energy to be released by the device. As a photoelectron is emitted from the bulk and absorbed by the detector, it is called a photoelectron. This

is a type of continuity that is rarely needed in practice.

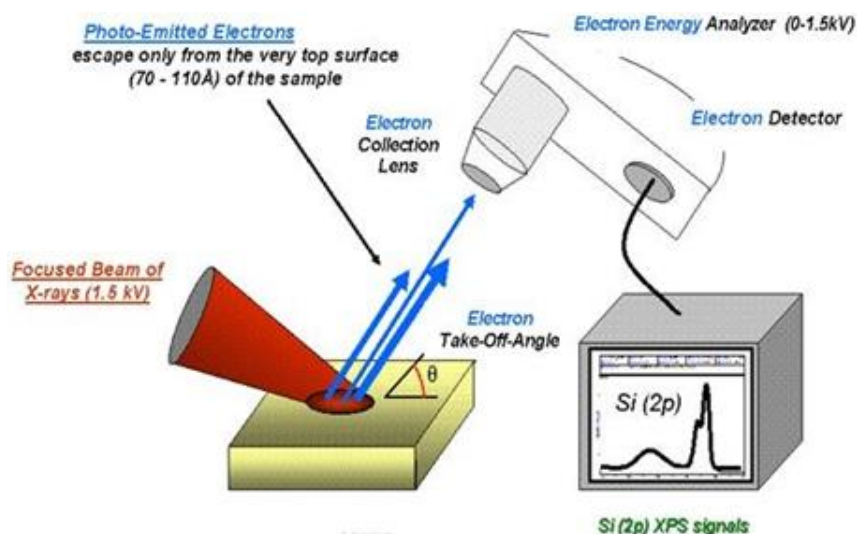


Fig. 5.3: Diagram of components of a basic monochromatic XPS system

(source https://www.net/figure/Schematic-diagram-of-XPS_fig9_319256244)

The number of electrons found in a given binding energy is plotted in a typical XPS spectrum. Each component generates XPS peaks, which are distinguishing characteristics. These peaks correspond to the electron configuration of the atoms' electrons, i.e. 1s, 2s, 2p, 3s, and so on. The number of electrons discovered at each peak is proportional to the number of elements present in the XPS sample size. Each raw XPS signal is corrected by dividing the intensity by the relative sensitivity factor and normalized to all detected elements to obtain the atomic percentage. Because no hydrogen is found, this atomic percentage rules out hydrogen.

5.3 SALT SPRAY TEST

Salt spray tests are performed in a closed test chamber. The saline solution is applied to the sample through a spray nozzle. This thick salt water fog is used to simulate a corrosion experiment. After a period of time depending on the corrosion resistance of the product, the form of the oxides is evaluated. The more stable the product, the longer it will take for the oxides to appear. For some coatings, the test period can range from 24 to 1000 hours or more.

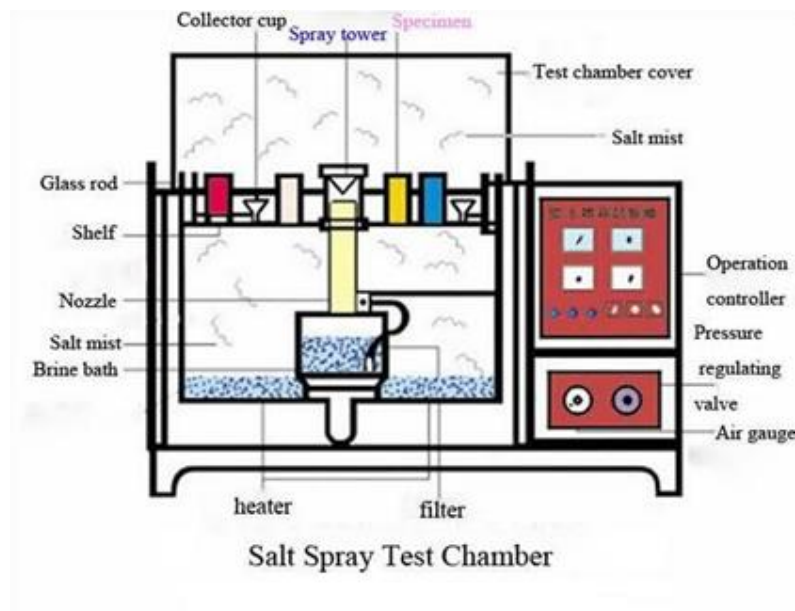


Fig. 5.4 Salt spray chamber and its elements

(source : <https://www.testlabs.my/salt-spray-test-chamber.html>)

The salt spray test is a simulation performed in a laboratory. It is used to test the ability of surface coatings to withstand weathering in an accelerated manner. This is one of the oldest test methods used in the manufacture of HVAC-R coatings, and as such, it is frequently mentioned when selecting HVAC-R coatings.

The salt spray process is carried out in accordance with ASTM B-117.

First, prepare small panels with the coating to be tested (typically 3 x 5 inches or 4 x 6 inches). Adhesive tape is typically used to secure the edges and back of the panels. The front of the panel is then “scratched” with a sharp instrument to remove the coating and reveal the metal substrate beneath.

Once the panel has been prepared, it is installed inside the test cabinet. The cabinet is equipped with posts that hold the panels in the ASTM B-117-specified position, which is tilted back 15-30 degrees from vertical.

The cabinet is then closed, and a 5 percent salt solution is fed into it at a constant rate and temperature using a sprayer. Salt fog is sprayed from above, causing the drops to fall and settle on the panels.

Following this stage, the test panels will be checked and monitored on a regular basis to ensure that the salt fog chamber is functioning properly. During this brief panel evaluation, it is determined whether the test passes as expected or whether the coating on the test panels fails prematurely.

5.4 IMMERSION TEST

Immersion tests track the progression of damage caused by prolonged immersion in a destructive environment, as well as other factors that hasten the degradation process.

These tests may include other drag or dip tests, such as cyclic tests. In addition, instrumentation such as electrochemical instrument connections may be included throughout to facilitate measurements.

Immersion tests can generate consolidated alloy damage data and are used in industries where diving conditions exist.

In general, immersion tests can be divided into:

- Alternative dip test- This immersion test involves a cyclic procedure in which the sample is immersed for a specified period of time. The sample is then removed and dried before being re-immersed in the cycle. As a rule, about a hundred cycles are performed during the test.
- Simple Immersion test- In this test, small batches of material are placed in the test environment and weight loss is calculated over a period of time.
- The immersion test remains the most reliable screening method. It also serves as the easiest and most cost-effective way to determine the most suitable damage protection material for a particular application.

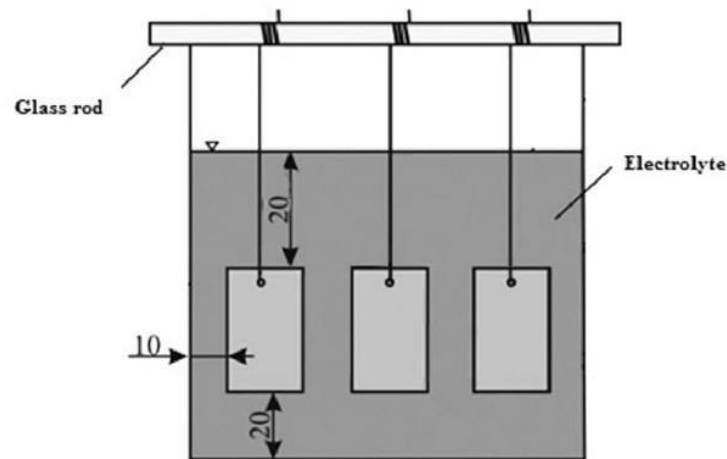


Fig. 5.5: Immersion test bath chamber

(https://www.net/figure/Immersion-test-apparatus-showing-samples-and-minimum-distance-requirements-in-mm_fig1_279291912)

5.4.1 Sample requirements for the immersion test of Cor-ten A588 steel

- Samples are usually round samples with a diameter of approximately 3 mm (0.125 inches), 8 mm (5/16 inches) or 11 mm (7/16 inches). Hole with mounting diameter 1/16 in.
- The cut edges of the specimens are often ground with sandy particles.
- The choice of laboratory tests is frequently determined by the environmental conditions to be simulated and the amount of acceleration required. Acceleration is achieved during immersion testing primarily as a result of : Prolonged exposure to critical conditions that are expected to cause damage. For example, if a vessel is to be treated with a chemical on a regular basis for 24 hours, 240 hours of corrosion exposure in the laboratory should be considered.
- Improve the conditions to increase the rate of damage, such as increasing the acidity, salt concentration, temperature, or pressure of the solution.
- Once the environmental conditions have been determined and the test has

been designed, it should be repeated enough times to determine if it meets the reproduction criteria.

5.5 WIRE CUT EDM

To achieve a specific gap, a CNC wire-cutting EDM machine applies impulse voltage to electrode wire and workpiece via impulse source controlled by a servo system, and then discharges impulses in the working liquid between electrode wire and workpiece. Before the workpiece can be shaped into the desired shape, a large number of small holes form due to the erosion of impulse discharging, as shown in figure.

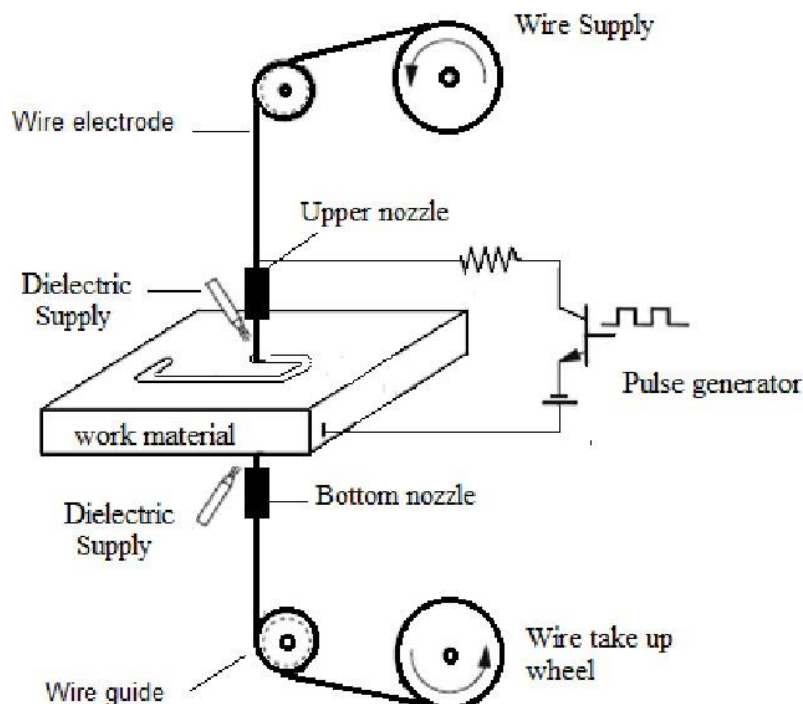


Fig. 5.6 Schematic representation of Wire cut EDM
(source: https://www.net/figure/Principle-of-Wire-cut-EDM1_fig1_315782856)

The cathode of the impulse power source is connected to the electrode wire, and the anode of the impulse power source is connected to the workpiece.

When the workpiece comes close to the electrode wire in the insulating liquid and the gap between them narrows to a particular value, the insulating liquid is broken through; a discharging channel forms quickly, and electrical discharge occurs.

The eroded workpiece cools quickly in the working liquid and is drained away, releasing massive high temperatures immediately, up to more than 10000 degrees Celsius

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CHAPTER 6

RESULTS AND DISCUSSION

6.1 IMMERSION TEST ON COR-TEN A588 STEEL

Here in this process, the corrosion rate of coated Cor-ten A588 steel and the Uncoated Corten A588 is found out by the immersion weight loss method

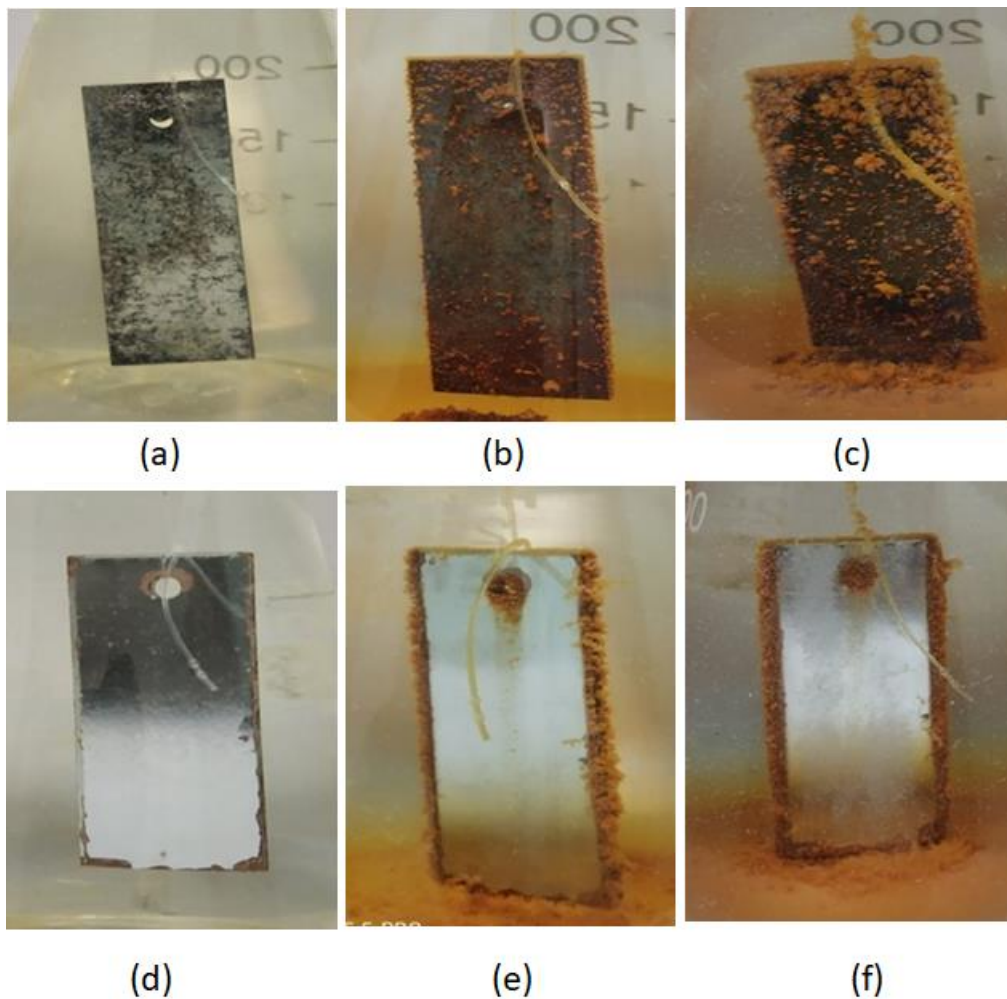


Fig. 6.1: Images of Cor-ten A588 steel immersed in 3.5% NaCl
(a)Raw Cor-ten A588 steel (b)Raw Cor-ten steel after 7 days (c)Raw Cor-ten steel after 14 days (d) Coated Cor-ten A588 steel (e) Coated Cor-ten A588 steel after 7 days (f) Coated Cor-ten steel after 14 days

These figures show images of coated and coated Corten steel material before and after immersion in 3.5% NaCl solution. Rust formation is very rare.

From the images above we are able to see the rust formation on the 7-day and the 14-day immersed Corten steel turns the sample into brown and it loses its silvery color due to the corrosion. In the image c we are able to see the Corten steel sample gets corroded and many of the rust particles or powder gets fallen off, This leads to the weight loss of 0.010 grams in the uncoated samples, while on the coated samples there is only minimal weight loss

Table 6.1: The weight loss analysis of Corten steel when dipped in 3.5 percent sodium chloride solution

Samples	pH of the solution		Conductance of the solution		Mean weight of the Samples		Weight difference
	Before	After	Before	After	Before	After	
Corten A588 steel	6.98	5.87	28.6	64.99	5.396	5.38	0.010

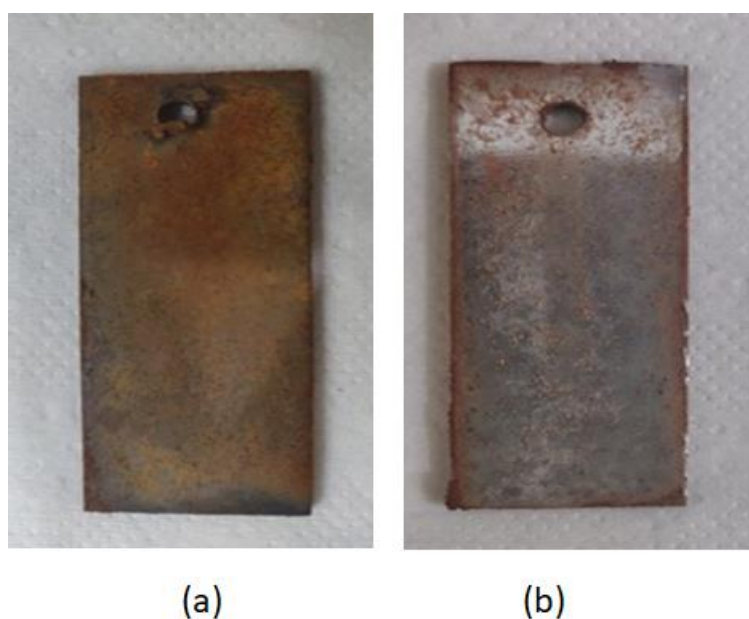
From the above table It is clear that the pH of the solution decreases so the conductance of NaCl solution increases which results in the dispersion of ions and mean weight of the sample slightly reduces.

When immersed continuously for 1-2 weeks, the rust formed on the dipped uncoated Corten A588 steel shows two separate layers, one layer loose and the other oily type rust (Paper 15). Due to the presence of other material (Tri coated Corten steel) the Cu Ni and Cr oxide layer did not form any more surface texture, and the surface analysis of the samples was performed with FESEM / SEM and XPS. It forms patches of amorphous phase, like a cotton ball, with similar observations and results in Raman's research paper.

Immersion test on Corten steel during the corrosion test, the increased concentration of oxygen accelerates the formation of oxides hydroxides and oxyhydroxides (paper 18), like these kinds of oxides and hydroxides are found in our research here, further more surface morphology and the presence of lepidocrocite, akageneite and traces of goethite are confirmed by using XPS and SEM analysis. These findings were also found and studied by N K Tiwary in his research paper.

6.2 SALT SPRAY TEST ON COR-TEN A588 STEEL

From the below figure, we can see that the Cor-ten A588 steel with no coating has been severely corroded, as a result, it has brownish-red rust on its surface. While the tri-layer (Cu, Cr, Ni) coated Cor-ten steel has witnessed very little corrosion. As we can see from fig(b), the steel sample has little to no rust on its surface.



***Fig 6.2: Cor-ten A588 steel sample after the salt spray test
(a) Non coated Cor-ten Steel (b) TRI coated Cor-ten steel***

Chloride is frequently found in environments containing akageneite (β -FeOOH), another form of iron oxyhydroxide. As the lepidocrocite converts to magnetite when the oxygen supply is low, the formation of magnetite can occur from the inside to the outer rust layers. Renato Altobelli Antunes, in his study also found similar findings.

It is possible to link the color of the oxide to a particular phase. Research has shown that the red oxide found is normal for lepidocrocites (γ -FeOOH). The yellow areas are lined with a mixture of lepidocrocite and gothite. Cr, Cu and Ni combine with oxygen before an oxide layer of iron is formed. This layer is highly corrosion resistant, preventing the formation of rust and protecting the underlying Cor-ten A588 metal steel surface.

In a salt spray test environment, a rust layer is observed to form rapidly on the surface of Cor-ten A588 steel, after which the rust layer becomes thicker and more compact. All rusty specimens are covered with a layer of brown, reddish rust. Moreover, the formation of a rust layer leads to a clear volume expansion of the specimens. Yu Zhang et al (2020) obtained similar results from his analysis in his research paper.

Due to the fact that very little damage has been done to the Cr, Cu and Ni coated core-ten steel, we can assume that the metal we can witness from Fig. (B) has corrosion resistance. The tri-layer coating of copper, nickel and chromium on the core surface of the core-ten A588 steel sample increased.

6.3 SEM ON COR-TEN A588 STEEL

Surface morphology of oxide layer created on Corten steel base metal and coated metal after immersion for on 2 weeks NaCl 3.5% solution is observed using SEM. At the top of the surface notable rust pit is formed which indicates a tightly packed oxide layer being produced. The oxide layer composed of lepidocrocite (γ -FeOOH), akageneite (β -FeOOH) and tracks of the Goethite (α -FeOOH) is droopily packed and by nature it is not very protective. lepidocrocite (γ -FeOOH) are observed as small sandy crystal structures or small flowery / fine plates like structures which is typical, these kinds of compound structures is also observed in the images Here Cotton ball globular structures Goethite (α -FeOOH) which are semi crystalline which are also observed in the surface morphology of the oxide layer. Rosette morphologies i.e., akageneite (β -FeOOH) which are also observed in the top oxide layer formed. Mindaugas Daukšys on his research study also found similar observation.

By this SEM analysis method, we are able to analyze the surface morphology and the corresponding particle size distribution was analyzed employing image software. Here the different stages of Corten steels have been observed and the result comparison is made.

6.3.1 Raw Corten samples before and after immersing on seawater

From the figures, we are able to figure out that the morphology of raw Corten microstructure possesses oxide layers with fluffy surface while the raw Corten after immersion has web like compact structure. After the immersion of Raw Corten steel the composition of the metal changes and there is huge change in weight percentage after this the Fe (49.3%) and O (43.06%) it changes to 1.04% of Fe and 9.98% of O and the weight % of Na and Cl increases by 30% and 40% respectively. Depending on the rust structure analysis, the SEM images of the rusted surfaces may have a different appearance and orange-yellow sand-black or anthracite colour, with the products primarily being lepidocrocite ($\gamma\text{-FeO (OH)}$), goethite ($\alpha\text{-FeO (OH)}$), and magnetite (Fe_3O_4).

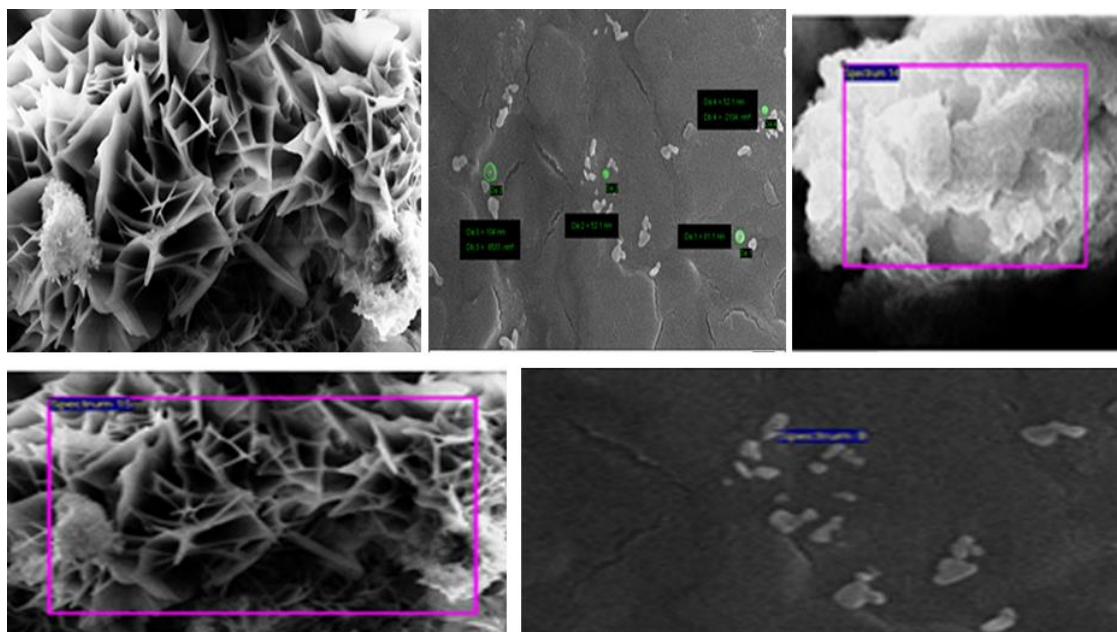


Fig. 6.3: SEM images of Raw Cor-ten A588 steel before immersed in 3.5% NaCl

When the corrosion resistance of the atmosphere improves and the mass ratio is greater than 1, the corrosion resistance of Corten steel is strongly dependent on

the crystalline α -FeOOH to all other ferrous oxides. Mindaugas Deuces also received a similar observation in his dissertation and the results from his analysis.

Table 6.2 : EDAX analysis of Corten A588 steel

Raw sample before immersion			Raw sample after immersion		
Element	Weight %	Atomic %	Element	Weight %	Atomic %
O K	46.08	73.29	C K	11.63	22.5
Na K	0.30	0.89	O K	9.98	14.5
Mg K	1.34	1.04	Mg K	1.86	1.79
Si K	1.03	0.93	Al K	0.21	0.18
Cl K	1.38	0.99	Cl K	42.84	28.1
Fe K	49.36	22.49	K K	0.54	0.32
			Fe K	104	0.43

The specific crystal structure of goethite and lepidocrocite is revealed by SEM analysis. The cotton ball structure of goethite crystals contrasts with the flower plate structure of other lepidocrocite crystals. He found similar results from the analysis of Renato Antonelli Anton's in his research paper. The iron phase undergoes a possible growth process.

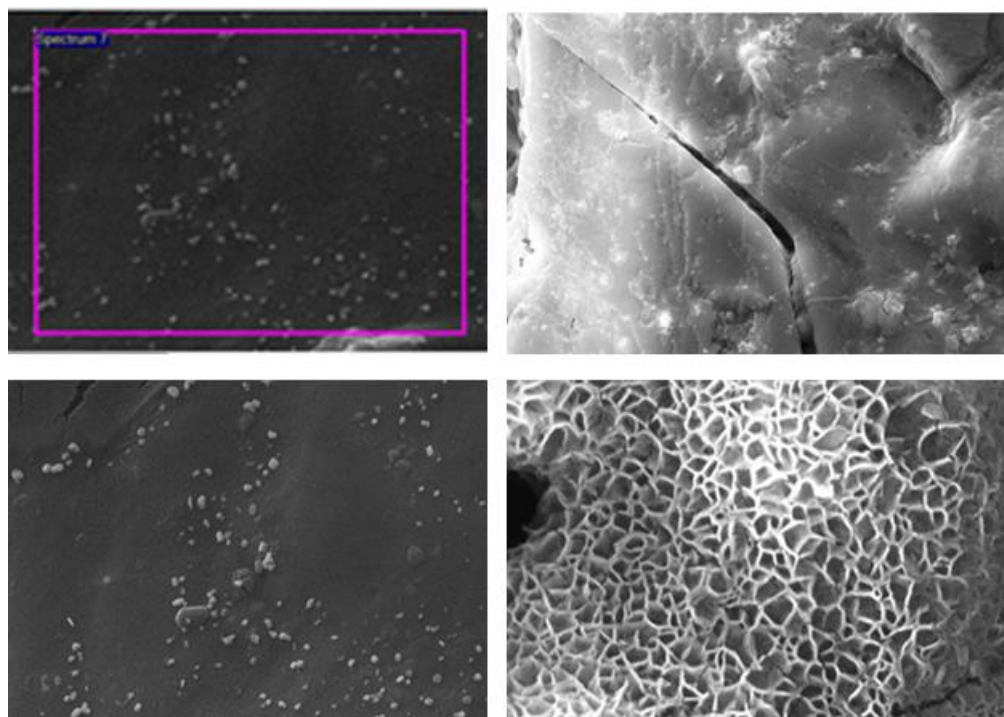


Fig.6.4 : SEM images of Raw Cor-ten A588 steel when immersed in 3.5% NaCl

A very fine moustache of α -FeOOH appears to form a layer-like foam and cloud on the upper surface of the rust in the early stages. As the exposure time increases, α -FeOOH becomes thinner and more viscous, forming sharp plates. Sai J Oha has found similar observations in his research paper. The complete crystallized form of α -FeOOH appears at a later stage. It has been observed that the shape of α -FeOOH can be seen in a sample at different destructive stages. R.E. Melchers et.al (2008) found similar results in his research paper. Here it is clear that the lepidocrocite (major) akageneite (minor) and gothite (minor) are loosely bound in the rust layer. Rust is a combination of iron compounds with an extra presence in the spinal stages as an important compound.

6.3.2 Coated Corten steel before and after immersion

Here in Corten steel coated after immersion in NaCl, the Cr concentration is higher in the inner corrosion layer, which results in the formation of α -FeOOH and doping of smaller glass structures Cr, T. Kamimura et.al (2016). Similar findings were made for research activities. The fine-FOOH in the rust layer improves the compaction of the rust layer and prevents rusting (Paper 2). In addition, the Cr density of the inner rust layer affects the characters of Corten steel, and Jiawei Yang et.al (2016) found a

Table 6.3 : EDAX analysis of Coated Corten A588 steel

Coated sample before immersion			Coated sample after immersion		
Element	Weight %	Atomic %	Element	Weight %	Atomic %
O K	17.92	43.3	Na K	4.37	4.32
Na K	0.32	0.53	O K	40.23	57.1
Mg K	0.96	1.51	Mg K	14.49	13.5
C K	4.51	14.30	Al K	0.70	0.58
Cl K	1.38	0.99	Cl K	26.23	46.8
Fe K	79.30	54.54	K K	1.54	0.95
			Fe K	7.24	2.95

similar observation in his scientific study. This effect is manifested by the amorphism of the inner corrosion layer due to the formation of ultrafine corrosion-product particles. Ultrafine corrosion-product particles containing amorphous $\text{Cr}(\text{OH})_3$, FeCr_2O_4 and some iron oxides may reduce the conductivity of the corrosion product and merge Cr with Fe to form a solid solution. At high solubility, some Cr converts Fe in iron oxyhydroxide to form $\alpha\text{-Fe}_x\text{Cr}_{1-x}\text{OOH}$, while some Cr accumulates at defects and grain boundaries.

Cu in Cor-ten A588 steel inhibits rust growth and prevents oxygen from reaching the steel surface. Cu reduces rust conductivity, which accelerates and coats the steel surface, preventing crystallization of the steel, uniform dissolution of the steel, and the formation of a rust layer at an early stage. Q.C. Zhang et al. (2002) discovered similar results and observations in his study.

Instead of distributing Ni everywhere in coated curtain steel, it mainly focuses on the inner film. Ni and Corten steel form a top layer, react with oxides and produce NiO and $\text{Ni}(\text{OH})_2$, and the rust layers have a smooth structure without flakes. The beneficial effect of Ni is that the damage gradually decreases as the amount of Ni in the steel structure increases. J R Deepak et.al (2019) found similar results from his analysis in his research work.

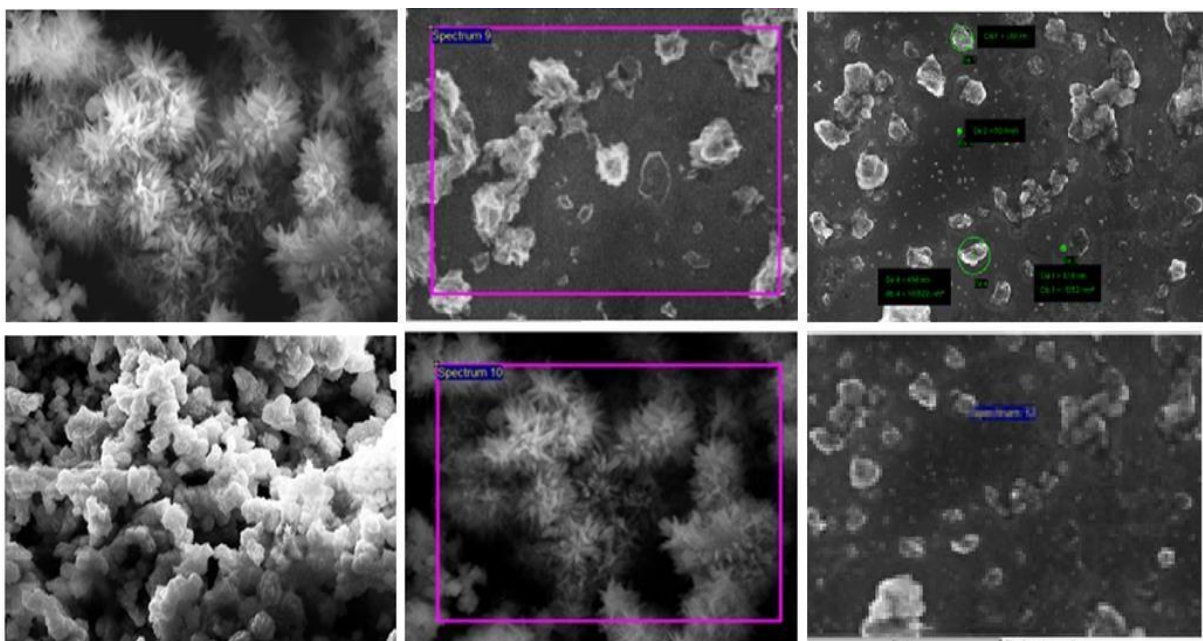


Fig. 6.5: SEM images of Tri coated Cor-ten A588 steel before immersing in 3.5 % NaCl

According to the SEM results, Cr is best observed in compact rust layers, whereas Cu and Ni are not concentrated in this layer. This is advantageous due to the high Cr content, which aids in the formation of a compact rust layer, and the steel's low carbon content, which reduces strain energy and the Fe₃C content, thereby increasing the corrosion resistance of FeO (OH), the main product of steel corrosion. It crystallizes into goethite α -FeO (OH) and lepidocrocite γ -FeO (OH) modifiers (OH). In an aggressive environment, these minerals are combined with magnetite Fe₃O₄. Because goethite-FeO (OH) and lepidocrocite-FeO (OH) Are Effective sorbents.

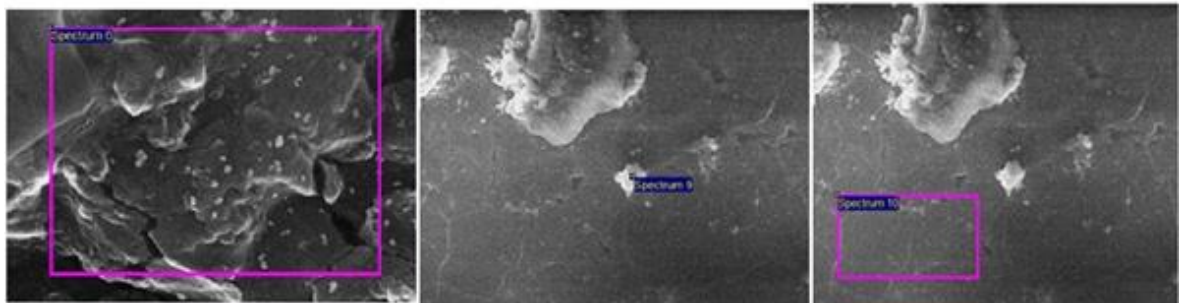


Fig. 6.6: SEM Image of Tri coated Cor-ten A588 steel after immersed in 3.5% NaCl solution

6.4 XPS ANALYSIS ON COR-TEN A588 STEEL

A broad spectrum was first identified to identify the surface elements of O, C, Cu, Ni and Fe using Xps analysis on raw Cor-ten A588 steel and crude powder. The mainly absorbed peak spectrum is then classified based on the reported spectrum of iron oxides. The main constituents of rust found on both surfaces were α -FeOOH and β -FeOOH. Amorphous γ -FeOOH is one of the elements found in the rust layer. Foreign elements O, Mg, Cl and K were found. Their content in dust corrosion was lower than that of raw Cor-ten A588 steel

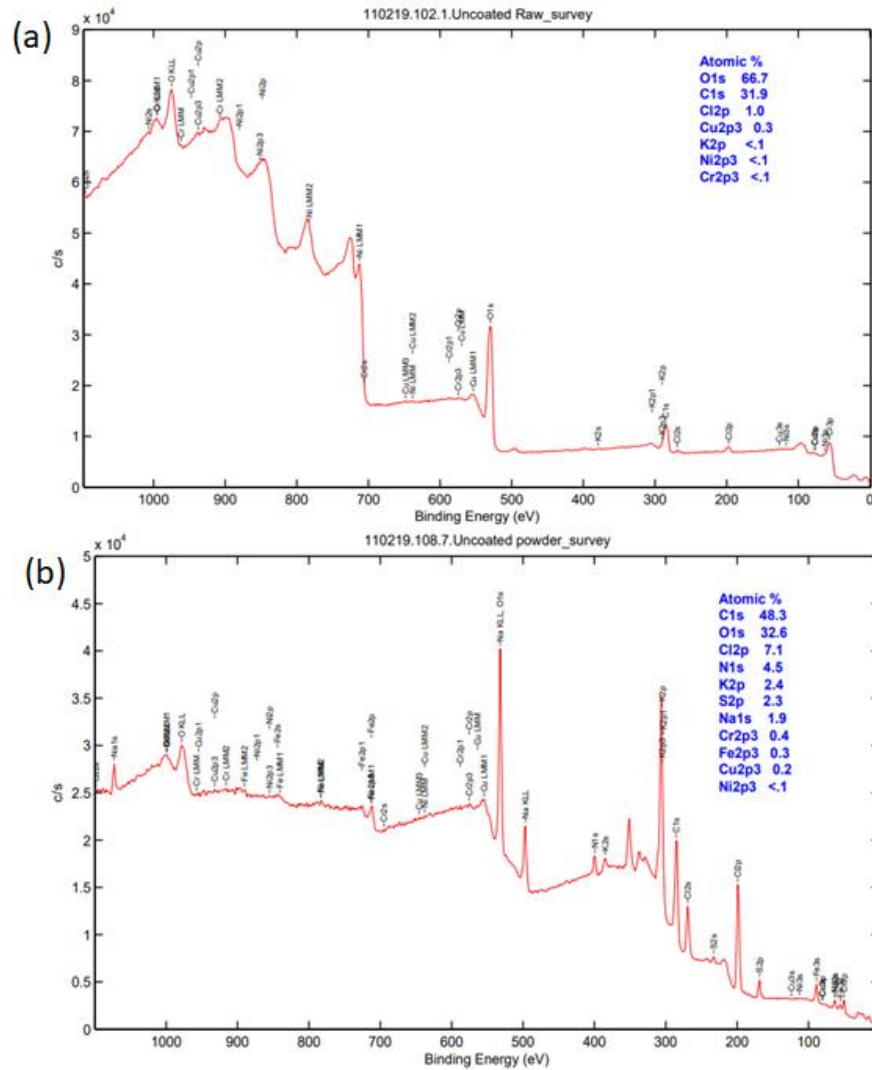
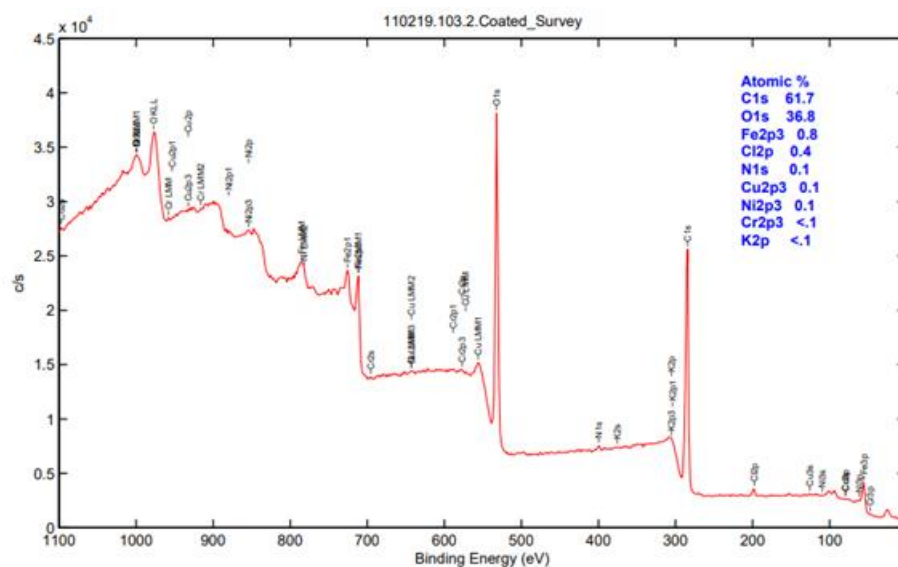
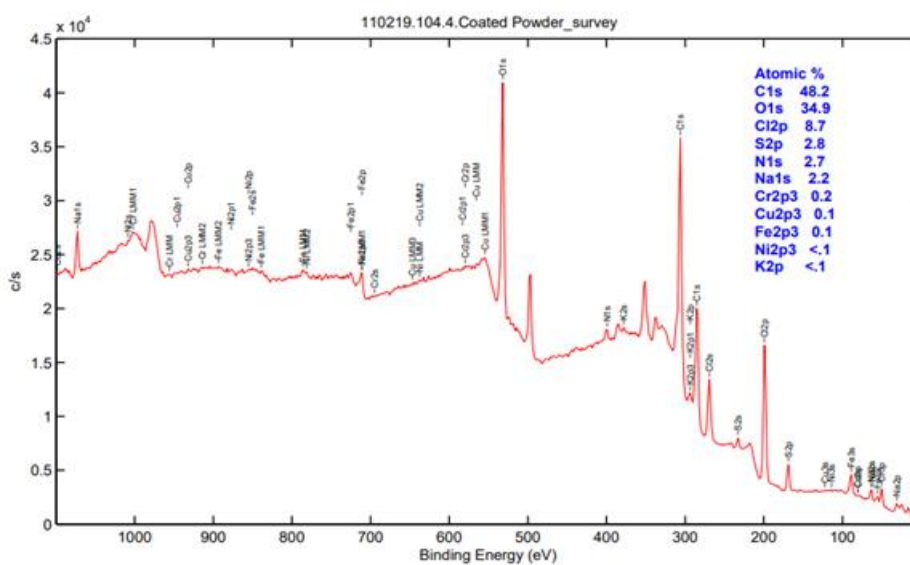


Fig 6.7: XPS plot of 14 days immersed uncoated Corten A588 Grade sample (a) Plate (b) Power deposited at the bottom (ions leached

Cl (chlorine) is one of the elements found. Chlorine (Cl) plays a major role in the destruction of Cor-ten A588 steel in NaCl solution. As the Cl content increases, so does the rate of damage. XPS analysis also revealed that the rust layer was composed of hematite (Fe_2O_3) and magnetite (Fe_3O_4).



(a)



(b)

Fig 6.8 XPS plot of 14 days immersed Ni - Cr - Cu tricoated Corten A588 Grade sample

(a)Plate (b) Powder deposited at the bottom (ions leached)

For coated raw and coated powder samples of Cor-ten A588 steel, the same analysis of XPS was used to determine the atomic percentage and chemical composition of the surface elements. In the coated raw sample and coated powder sample, C has a higher atomic percentage.

followed by O and Fe at very low concentrations (0.8%) and Cu Ni Cr at very low values. In the XPS spectrum, we can see that some CuO and Cr₂O₃ compounds are found in the rust layers. The concentrations of the C and O elements gradually decrease with increasing sputtering time, while the concentration of the Fe element increases with increasing depth, which results in a decrease in oxide level and exposure to the substrate. Yang Guo found a similar observation in his study.

This means that these compounds promote more or less protective rust layers in the Cor-ten A588 steel sample in an aqueous (3.5% NaCl) state. These results also suggest that Y.S. Choi's research paper.

We can see that the amount of O in the powder material is higher and the amount of C in the coated raw material is higher than that of O, which means that due to the Ni Cu Cr (tri-layer) coating it is much more resistant than normal Cor-ten A588 Steel.

6.5 SUMMARY OF RESULTS

In this research study, immersion test and salt spray test were performed to determine the degree of damage to coated and uncoated Cor-ten A588 steel. Further SEM and XPS analysis were performed to study the surface structure and elemental structure of the coated and uncoated Cor-ten A588 steel.

After 14 days of immersion testing, the coated samples lost 0.010 g of weight, while the coated samples weighed less. From the weight loss analysis, the conductivity of the NaCl solution increases as the pH of the solution decreases, which leads to the diffusion of the ions and a slight decrease in the average weight of the sample. When immersed continuously for 1-2 weeks, the rust formed on the dipped uncoated Cor-ten A588 steel shows two different layers, one layer of loose layer and the other of the greasy type inside. In other materials (Tri coated Corten steel) is not formed due to the presence of Cu Ni and Cr oxide layer. After surface analysis, we see that it produces patches of amorphous phase like cotton ball., High concentration of oxygen promotes the formation of oxide hydroxides and

oxyhydroxides. SEM and XPS analysis confirm the presence of lepidocrocite, akageneite, and goethite residues.

In the salt spray test, the uncoated cor-ten steel is severely corroded, resulting in brownish-red rust on its surface. Tri-layer (Cu, Cr, Ni) coated cor-ten steel witnessed very little damage. Chloride is frequently found in environments containing akageneite (β -FeOOH), another form of iron oxyhydroxide. As the lepidocrocite converts to magnetite when the oxygen supply is low, the formation of magnetite can occur from the inside to the outer rust layers. The red oxide detected is normal for lepidocrocites (γ -FeOOH). The yellow areas are lined with a mixture of lepidocrocite and goethite. Cr, Cu and Ni combine with oxygen before an oxide layer of iron is formed. This layer is highly corrosion-resistant, preventing the formation of rust and protecting the underlying Cor-ten A588 metal steel surface.

However, the structure changes after immersion of this coated Cor-ten A588 steel, increasing the weight of O from 36.67% Na to 14.31% Cl to 25.79% and Fe to 17%. This is the change in percentage of the weight of the coated Cor-ten A588 steel when immersed in 3.5 percentage NaCl solution. In Cor-ten A588 steel coated after immersion in NaCl, the inner rust layer has a higher Cr density. The fine-FOOH in the rust layer improves the compaction of the rust layer and prevents rusting. Ultrafine corrosion-product particles containing amorphous Cr (OH) 3, FeCr₂O₄ and some iron oxides may reduce the conductivity of the corrosion product and merge Cr with Fe to form a solid solution. Some Cr converts Fe in iron oxyhydroxide to form α -Fe_xCr_{1-x}OOH at high solubility, while some Cr accumulates at defects and grain boundaries. The presence of Cu in Cor-ten A588 steel inhibits rust growth and the supply of oxygen to the steel surface. Cu reduces rust conductivity, which accelerates and covers the steel surface, preventing rust crystallization.

According to the SEM analysis, Cr is best observed in compact rest layers, whereas Cu and Ni are not concentrated in this layer. The high Cr content of steel is advantageous because it aids in the formation of a compact rust layer, and the low carbon content of steel reduces strain energy and Fe₃C content, thereby increasing the steel's corrosion resistance. The main product of steel corrosion is FeO. (OH).

In the XPS analysis of raw Cor-ten A588 steel and raw powder, a broad spectrum was first identified to identify the surface elements of O, C, Cu, Ni, and Fe. The main constituents of rust found on both surfaces were α -FeOOH and β -FeOOH. Amorphous γ -FeOOH is one of the elements found in the rust layer. Foreign elements O, Mg, Cl and K were found. Their content in dust corrosion was lower than that of raw Cor-ten A588 steel.

One of the elements discovered is Cl (chlorine). Chlorine (Cl) plays a major role in the destruction of Cor-ten A588 steel in NaCl solution. As the Cl content increases, so does the rate of damage. XPS analysis revealed that the rust layer contained hematite (Fe_2O_3) and magnetite (Fe_3O_4). In the coated raw sample and coated powder sample, C has a higher atomic percentage, followed by O and Fe at very low concentrations (0.8%) and Cu Ni Cr at very low values. In the XPS spectrum, we can see that some CuO and Cr_2O_3 compounds are found in the rust layers. The concentrations of the C and O elements gradually decrease with increasing sputtering time, while the concentration of the Fe element increases with increasing depth, which results in a decrease in the oxide level and exposure to the substrate.

In powder materials, the amount of O is higher, but the amount of C in the coated raw material is higher than that of O, which means that because of the Ni Cu Cr (tri-layer) coating it is much more resistant than ordinary Cor-ten A588 steel. Therefore, we can assume that the corrosion resistance of the metal is increased due to the tri-layer coating of copper, nickel and chromium on the core-ten steel sample surface, and this can be used to further enhance reliability and damage. Defensive properties of Cor-ten A588 steel in various industrial and marine applications.

CHAPTER 7

CONCLUSION

From the results and analysis, that we got from conducting corrosion tests like Salt spray test and Immersion test, we can conclude that tri-coated (Cr Cu Ni) Cor-ten A588 steel have better corrosion resistance properties than regular Cor-ten A588 steel. Some of the findings that we got from corrosion tests are characterized and analyzed through FESEM and XPS analysis. They are given below ;

- From the weight loss analysis, the conductivity of the NaCl solution increases as the pH of the solution decreases, which leads to the diffusion of the ions and a slight decrease in the average weight of the sample. After 14 days of immersion testing, the coated samples lost 0.010 g of weight, while the coated samples weighed less.
- In the salt spray test, the uncoated Cor-ten A588 steel is severely corroded, resulting in brownish-red rust on its surface. Tri-layer (Cu, Cr, Ni) coated Cor-ten A588 steel witnessed very little damage. Chloride is frequently found in environments containing akageneite (β -FeOOH), another form of iron oxyhydroxide.
- From the SEM analysis, we can see that a noticeable rust pit has formed on the upper surface, indicating that a tightly packed oxide layer is being produced. The oxide layer contains residues of lepidocrocite (γ -FeOOH), akageneite (β -FeOOH) and goethite (α -FeOOH), which are droplet-bound and non-natural preservatives.
- From the XPS analysis of raw Cor-ten A588 steel and raw powder, a broad spectrum was first identified to identify the surface elements of O, C, Cu, Ni, and Fe. The main constituents of rust found on both surfaces were α -FeOOH and β -FeOOH. Amorphous γ -FeOOH is one of the elements found in the rust layer. Foreign elements O, Mg, Cl and K were found. Their content in dust corrosion was lower than that of raw Cor-ten A588 steel.

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