**A Review on Corrosion over Superheater Materials and coatings by Various Methodologies**

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**Abstract.** Power plants represent a significant sector for the generation of energy for commercial and industrial applications, benefiting humanity in several ways. Power plants consist of many components, including a superheater, economizer, condenser, air preheater, and reheater. The components in the power plants will experience roughly 600°C, necessitating the use of superheater materials for these components. Despite the utilization of such materials, components frequently fail owing to oxidation, corrosion, and erosion resulting from scale development, sulfur attack, aging, and cracking at bends. Numerous studies continue to address these issues, and this research provides an opportunity for scholars to understand the latest trends in boiler materials aimed at enhancing corrosion-erosion resistance and facilitating the formation of protective oxidation layers during oxidation. This paper elucidates the new research conducted on the corrosion of superheater materials to address deficiencies in boilers and power plants.

**Keywords:**

Boiler materials, Corrosion, OCP, Electrostatic potentio-dynamic tests, super heater materials, SEM, EDX, XRD.

**1.** **Introduction**

Thermal power plants are fundamental to large-scale energy generation, particularly by employing steam generated from boiling water to supercritical temperatures. In these systems, water is subjected to severe heating in the boiler, resulting in its conversion to superheated steam. The high-energy steam is subsequently expanded in turbines, generating rotating motion that powers electrical generators to create electricity. The steam, subsequent to traversing the turbine, is condensed into water within a condenser and recirculated, constituting the Rankine cycle, a fundamental thermodynamic cycle for steam power generation.

The operation of thermal power plants, however, presents several environmental concerns. The combustion processes result in the release of pollutants, including nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter such as fly ash, which contribute to air and dust pollution. These emissions, along with noise pollution, land degradation, and soil quality deterioration, provide substantial environmental risks, as seen in Figure 1. Resolving these challenges necessitates thorough research, and the Environmental Impact Assessment (EIA) boards have evaluated and suggested improved technology for pollution control to alleviate the effects.



**Fig 1. Possible problems in super heater materials**

A vital element of thermal power plants is the generation of superheated steam, necessitating the heating of water in the boiler to temperatures exceeding the critical point, generally around 723°C. The boilers and related equipment are fabricated from materials with exceptional thermal stability to endure harsh heat conditions. These materials, also known as superheater materials, are particularly designed for their outstanding thermal resistance. Their endurance is due to elements including chromium, boron, aluminum, and nickel, which improve the material's capacity to withstand high temperatures while preserving structural integrity.

Nonetheless, several materials lack the necessary thermal and mechanical qualities. Consequently, sophisticated materials science methods, including heat treatment, surface modification, and alloying, are utilized to intentionally impart these advantageous features. These strategies improve the thermal performance of materials, increasing their resistance to prevalent concerns such as oxidation, corrosion, and erosion, which are the primary degradation processes in thermal power plants. It is crucial for superheater materials to withstand degradation over extended working durations to preserve efficiency and reliability.

Researchers have extensively investigated contemporary modification approaches, including as surface coatings and high-temperature alloying, to further reduce oxidation and corrosion-erosion. These methodologies are essential for augmenting the protective characteristics of superheater materials, enabling them to preserve their efficacy under hostile thermal and chemical conditions. Current research in material modifications seeks to enhance the longevity of essential components while minimizing maintenance expenses and operating interruptions, which are crucial for maximizing the long-term sustainability of thermal power plants.

**2. Significance of Corrosion**

Corrosion is a significant problem in high-temperature environments, mostly caused by the development of oxides, hydroxides, and sulfides, as seen in Figure 2. Corrosion renders the material structurally unstable, resulting in component failure and necessitating replacement, hence incurring additional expenditures. This results in financial loss, prolonged component replacement time, and associated labor expenses. Moreover, high-temperature applications may lack efficiency owing to material degradation, as seen in Figure 3, which is mostly attributable to the significant problem of corrosion.



**Fig 2. Deposit of corrosive materials**

Surface modification is an effective way to mitigate the challenges posed by corrosion. The majority of studies employed this approach (surface modifications-coatings) utilizing varying quantities of resistive coatings through different alloying elements to achieve the necessary thermal, physical, and chemical characteristics. Various techniques were employed to elucidate these adjustments and research efforts, including potentiodynamic polarization, open circuit potential, and thermal cyclic loading, among others.



**Fig 3. Corrosion in feed water pipes**

**3. Necessity of Corrosion study methods**

The study of corrosion is critical in high-temperature applications, since it significantly influences the majority of issues encountered in component performance. This investigation will identify connected issues such as pitting, sulfur attack, corrosion, and material failure that necessitate replacement or repair efforts. The issues arose from inadequate demineralization, since fluctuating pH results in material degradation and the development of sulfides, oxides, and hydroxides that create a surface layer, compromising the thermal characteristics of components. Fly ash contributes to the infiltration of sulfur in components, frequently resulting in perforations and leaks inside power plant infrastructure. Gases like ammonia and chlorine render the material unstable. The principal challenges impacting socio-economic factors and environmental concerns in managing high-temperature applications and their components raise questions about safety.

**4. Corrosion study methods – an overview**

Corrosion properties were examined using methods including potentiodynamic polarization, open circuit potential, and thermal cyclic loading using surface-modified materials.

1. Potentiodynamic polarization is the technique employed to assess the corrosion resistance of the specified material. Surface-modified specimens and unmodified specimens were evaluated using this approach, focusing on the impact of surface alterations on corrosion resistance. This approach involves delivering current through the electrolyte while altering the electrode potential of the materials under examination. The instrumental configuration is depicted in Figure 4.



**Fig 4 Potentiodynamic polarization test method**

1. Thermal cyclic loading is a method employed to simulate high-temperature conditions, such as those found in boilers, on both surface-modified and base materials to assess weight gain or loss and to describe them using techniques such as SEM, EDX, XRD, and elemental mapping. This approach is predominantly utilized since it yields conclusions on the surface changes implemented for the analysis of corrosion resistance.
2. The open circuit potential is a passive technique for examining the corrosion resistance of the working electrode in relation to the reference electrode, as seen in Figure 5. This approach measures solely the resting potential, hence it is sometimes referred to as zero current potential.



**Fig 5 Open circuit potential test method**

1. The Linear Polarization Resistance technique is utilized to determine corrosion rate data and Rp by applying external current to assess oxidation and corrosion, as described by the Stern-Geary equation, which is directly related to this process. Figure 6 illustrates the configuration and data validation.



**Fig 6 Linear polarization resistance test method**

1. Electrochemical Impedance Spectroscopy is a sophisticated technique employed to determine the impedance of a system functioning at alternating current potential frequency. This approach employed a working electrode (the material under resistance evaluation), an auxiliary electrode, and reference electrodes to investigate corrosion rate and resistance phenomena. Figure 7 illustrates the instrumental cluster pertinent to this research methodology.



**Fig 7 Electrochemical Impedance Spectroscopy test method**

1. Various non-electrochemical testing methods, including electro-reflectance spectroscopy, vibrational spectroscopies, X-ray absorption and scattering spectroscopies, scanning probe techniques, and weight loss/gain assessments, are available to investigate corrosion features.

**5. Review of recent several research work on corrosion study**

The hot corrosion and oxidation behavior of superalloys, including Superni 75, Superni 718, and Superni 800H, at 900°C in both air and a salt environment (Na2SO4-60% V2O5) was examined. [1]. For experimental purposes, the substrate was fabricated into a specimen of 20 x 15 x 5 mm and meticulously polished using several grades of grit sheets. The investigation was conducted under a saline environment (Na2SO4-60% V2O5) with thermal cyclic loading for one hundred hours (one hour each cycle). Characterization techniques employed to investigate hot corrosion and oxidation features included FESEM, EDAX, X-ray mapping, and weight gain/loss analysis. The authors concluded from the study and comments that Superni 75 has superior resistance to corrosion and oxidation at 900°C in an air environment, attributed to the development of oxides of Ni, Cr, and Fe. Additionally, Superni 800H indicates somewhat worse resistance compared to Superni 75.

Reinforcement steel bars in concrete were subjected to experimentation via accelerated corrosion testing, current density measurement, and corrosion rate assessment using the CPR technique [2]. For this experiment, the characteristics of NaCl were examined at concentrations of 0%, 4.5%, and 5%. For corrosion resistance, 5% and 15% meta kaolin were designated as the binders. The examples consist of concrete cylinders measuring 100 x 200 mm, with 16 mm diameter steel bars positioned centrally. In the concrete sample, meta kaolin is included at 5% and 15% by weight of the total binders, together with the requisite quantities of NaCl. No reinforcement was used for electrical resistance.

The concrete specimens were examined using electrochemical testing over a 28-day period, revealing a rapid rise in current density upon fracture propagation. The LPR technique was employed to determine corrosion current density, utilizing PCLPR at low potential, from which current density was derived using the Stern-Geary formula based on observed polarization resistance. Two holes were made in the concrete for electrical resistivity measurements, which were then fitted with probes. An alternating current was applied, and resistivity was then assessed. The scientists determined that specimens containing 15% meta kaolin exhibit the longest time to failure, a 50% reduction in corrosion rate, and enhanced electrical resistivity compared to other combinations, since lower electrical resistivity correlates with increased corrosion rate.

Investigation of corrosion behavior and microstructure of 304L stainless steel subjected to one or more passes of gas tungsten arc welding (GTAW) [3]. The microstructure of 304L stainless steel is characterized using optical microscopy, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), X-ray diffraction (XRD), and hardness is assessed by Vickers hardness testing. A corrosion investigation was conducted utilizing possible dynamic polarization and emission testing methods. Samples measuring 200 x 100 x 6 mm were prepared and processed according to the laboratory protocol for the study. Electrochemical investigations were conducted by cross-sectioning the specimen to analyze the weldments in relation to the base, utilizing conventional colonel electrodes and graphite rods as references. Measurements were conducted upon the establishment of stable OCP. For the immersion test, samples were subjected to H2SO4 at 25±10°C for 48 hours to examine the morphology of the corroded surfaces. The investigation and discussions concluded that an increase in the number of weld passes correlates with a rise in delta ferrite, accompanied by a dendritic microstructure and skeletal architecture, which in turn enhances corrosion resistance. As the quantity of passes diminished, corrosion resistance decreased.

Experimentation with alumina forming austenitic stainless steel at 1173K in molten sodium sulfate and studied their hot corrosion behaviour through characterization techniques such as SEM, EDS, and XRD [4]. Alloy ingots were fabricated by re-melting and casting into dimensions of 10 x 10 x 100 mm, subsequently homogenized at 1200 to 1250 °C, and then cold rolled by 30 to 40%. Subsequently, recrystallization at 1200 to 2500°C for 5 to 10 minutes is conducted to regulate grain size between 20 and 30 micrometers. Corrosion testing was conducted using specimens of 80 x 8 x 1.2 mm, and to evaluate their behavior, nickel-based superalloys K438 and K417 of identical dimensions were selected. The cumulative testing duration was 100 hours across 9 cycles, during which specimens were extracted, cooled, weighed, and re-coated with salt for each cycle. Following the characterisation and discussions, the scientists determined that the novel AFA steel exhibited more stability than the two nickel-based superalloys. The corrosion resistance arises from a thin layer of aluminum oxide, succeeded by a thick chromium oxide layer generated during oxidation, which serves as a barrier to sulfur infiltration.

Studies of the hot corrosion behaviour of nickel-based superalloys were carried out by using coated along with uncoated specimens of IN738 LC and CM 247 LC in chloride and vanadium environments [5]. To provide a corrosive environment, Na2SO4, NaCl, and V2O5 salt baths were employed. Experimentation is conducted in a furnace using samples of specified laboratory size for thermal cycling at 700°C and 900°C. Characterization is conducted using scanning electron microscopy and energy-dispersive spectroscopy (EDS). The weight gain/loss approach involves graphing exposure time against weight, utilizing findings from the characterisation and oxidation kinetics of CM 247 LC resist corrosion followed by IN 738 LC.

Investigation of the effect of the salt mixtures with three variants in superalloy IN718 at both 550 and 650°C and gives a conclusion regarding their corrosion behaviour at those elevated temperatures [6]. In this work, the authors prepared three distinct salt mixtures: the first consisting of 100 wt. % NaCl, the second including 75 wt. % Na2SO4 and 25 wt. % NaCl, and the third containing 90 wt. % Na2SO4, 5 wt. % NaCl, and 5 wt. % vanadium oxide, along with respective specimens. For the experimentation, specimens were fabricated in a disc form, measuring 15 mm in diameter and 2 mm in thickness. Following exposure to temperatures of about 550 and 6500°C, the corrosion kinetics were analyzed using characterisation methods. Consequently, the authors concluded that the entire investigation adheres to parabolic kinetics. The unadorned specimen exhibits no alteration in weight. Chlorides create pits and cavities that provide access for corrosive agents. Type 1 demonstrates the most corrosion owing to its penetrating capability at elevated temperatures, whereas Type 2 shows no significant alteration at 550°C and exhibits mild corrosiveness at 650°C. Type 3 exhibits reduced corrosiveness at both 550°C and 600°C.

Experimental studies on low alloy ferritic steel were done with Ni-50 Cr coatings at two different temperatures such as 550 and 650°C [7]. Thermal cycling was examined in conjunction with varying concentrations of carbon dioxide, namely 0, 15, and 25 volume percentages. For experiments, samples of 30 x 30 x 4.5 mm of wire, produced by laboratory testing procedures, were utilized as powder and feed for the HVOF process. The samples were subjected to testing in the furnace at 550 and 6500C under various gas mixture settings, including air, (air + CO2 15%), and (air + CO2 25%), followed by thermal cyclic measurements. Utilize X-ray diffraction, scanning electron microscopy (SEM), and light microscopy for image analysis to assess porosity in sample characterisation. The scientists determined that there is no indication of substrate deterioration even at 6500°C in a high carbon dioxide atmosphere of 25%, and that weight changes are minimal compared to uncoated substrates, since the coated substrate exhibits no fractures during decontamination.

Experimentation and study of the boiler tubes coated with IN625 and IN686 by exposing them to waste incineration ashes [8]. Subsequently, SEM and EDAX elucidate distinct corrosion mechanisms, followed by X-ray diffraction to unveil the surface corrosion process that facilitates the creation of CrO2 and NiO. The authors indicated that the presence of Fe in the clad weld results in the creation of Fe2O3. The introduction addressed many uses of nickel-based superalloys, including IN625 and IN686.

For experimental purposes, samples measuring 20 x 5 x 1.5 mm of boiler pipes constructed from 16Mo3 Steel were sectioned and coated with IN625 and IN686, thereafter subjected to a temperature of 650°C for 1000 hours in waste incineration ashes. X-ray research indicates that the principal phases in ashes are CaCO3 and SiO2, while characterization techniques reveal that a protective layer composed of a combination of Cr2O3 and NiCrC2O3 in IN625 forms a thin film of NiO, Cr2O3, and Cr2O2, safeguarding the material from detrimental ashes. In the IN686 cladding method, the rate is somewhat slower, although it results in enhanced structural uniformity.

An experimental study about different boiler materials such as 13 Cr Mo (4-5), P91 (1.49), and P91 (1.45) was done in a biomass fixed grate furnace [9]. The study utilized chemically untreated woody chips and waste wood as fuel for 13 Cr Mo (4-5), P91 (1.49), and P91 (1.45) correspondingly. The probing approach was employed to assess the corrosion rate and mass loss. Operating temperatures were sustained between 740°C and 900°C with a consistent input power. Mass loss probes were utilized to acquire corrosion data for the assessment of measurement error. Experimentation was conducted in two phases: the initial phase and the variation phase. During the initial phase, both probes and furnaces were kept at a constant temperature, while in the variation phase, the temperature of the probes was altered. Deposit probes were employed to assess the deposition of fly ash. Through experiments involving two distinct fuels and phases, the authors concluded that corrosion rates were influenced by sustaining the steel surface temperature at 450°C for 13 Cr Mo (4-5) and between 400°C to 560°C for P91 (1.49) and P91 (1.45), alongside a flue gas temperature ranging from 740°C to 900°C for all conditions. P91 (1.49) has a lower mass loss and corrosion rate of 34% for wood chips, whereas waste wood displays 55%. Other materials demonstrate a greater corrosion percentage at elevated temperatures. P91 (1.45) has superior corrosion resistance, whereas 13 Cr Mo (4-5) demonstrates susceptibility to corrosion at low temperatures due to the presence of chlorides in both materials.

Pitting corrosion studies were made on 13 Cr Steel by using simulated boiler water which contains chloride and sulfide ions [10]. Specimens were fabricated to dimensions of 25 x 152 mm³ from 13 CR Steel, which underwent oil quenching followed by tempering. The laboratory preparation has been completed. The test water was prepared using procedures including all volatile treatment and oxygenated treatment. The test water was prepared in three proportions: 100 PPM chloride with 0 PPM sulfide, 100 PPM chloride with 50 PPM sulfide, and 100 PPM chloride with 100 PPM sulfide. An electrochemical corrosion test was conducted utilizing specimens as working electrodes, platinum as the counter electrode, and KL Ag-AgCl as the reference electrode. The study examined the behaviors of potential dynamic, potential-static, and pit growth, concluding that water with 50 PPM sulfide inhibits pit growth, but 100 PPM sulfide promotes it, attributed to the breaking of salt films and the degradation of salt coverings at pit openings.

Investigation of erosion-corrosion study with the help of **Ni-20Cr** cold sprayed SAE213 T22 and SAE516 grade 70 Steel were made at 750°C for 15 cycles [11]. Each cycle comprises 100 hours of heat loading followed by a 1-hour cooling period. Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), and X-ray Diffraction (XRD) were employed as characterization techniques to analyze the specimens about erosion-corrosion. Specimens measuring 20 x 15 x 5 mm were created using emery polishing and wheel polishing using alumina suspension. Thermal cyclic experiments were conducted. Three types of powders, namely Ni, P2, and Cr, were synthesized using a planetary ball mill for coating applications, employing the cold spray technique for the deposition process. Investigators concluded from the characteristic examinations that the coated specimens, displaying a lamellar splat-like microstructure, had a hardness increase of 2.5 times compared to the specimens, which demonstrated superior erosion-corrosion resistance due to the Cr2O3 layer.

Investigation of corrosion behaviour microstructure and tensile strength were made at a similar joint on nickel-based superalloys IN625 and IN78 [12]. The PCGTAW technique was used for dissimilar welding, utilizing 1.6 mm diameter ErNiCrMo-4 and ErNiCrMo-10 filler rods. The super alloy specimens were fabricated into plates measuring 175 x 55 x 5 mm using the WEDM method. Welds were executed using a single V groove of typical proportions. Subsequently, DDT (NDT) was conducted to identify any defects, confirming the absence of faults. Following this, a mechanical test was performed, demonstrating that the weldments exhibit ductility. For the metallurgical analysis, the welded specimens were machined cross-sectionally to get specimens measuring 28 x 10 x 5 mm. The cross-sectional regions were prepared for metallurgical analysis. Consequently, the surface of the weldment, IN718, displays an unmixed zone next to the weld interface, together with remnants of Ni-Mo-rich phases in the interdendritic area. Cyclic hot corrosion experiments were conducted by reducing the specimens to dimensions of 10 x 10 x 5 mm, utilizing a Na2SO4 + 60% V2O5 molten salt for about 50 cycles. The results indicate that IN625, when combined with the ErNiCrMo-4 filler rod, exhibits superior corrosion resistance; conversely, IN718 experiences more corrosion owing to spallation and increased weight gain compared to IN625. Consequently, the authors advocate for the use of ErNiCrMo-4 filler material.

A review of 111 journals about the high-temperature corrosion behaviour of superalloys in various molten salts such as chlorides, nitrates, sulphates and chlorides were made for effective input for future research [13]. As it is a recognized technique in energy conversion, several authors worldwide have conducted experiments on various alloy compositions at temperatures between 600 and 900°C, in conjunction with diverse corrosive conditions. The characterisation of the experimental was mostly conducted using gravimetric SEM, EIS, potentiodynamic polarization, and OCD. The author concludes that numerous researchers have made significant efforts to address the issues of corrosiveness, with several arriving at similar conclusions. Ultimately, thorough research interpretation combined with experimental studies may yield a new alloy suitable for harsh corrosive environments.

The corrosion behaviour of Steel used in concrete which is exposed to a pore solution of chloride and sulphate ions by means of EIS, OCP, LPT and also CTV was determined in both the simulated solution by combining current density and half-cell potential [14]. The investigation was conducted through specimen preparation followed by experimentation. Specimens were fabricated to dimensions of 16 mm in diameter and 10 mm in length, polished with abrasive materials, and prepared for electrochemical testing by soldering a copper wire to one side while the opposite side was coated with epoxy resin. The epoxy resin solution was made using distilled water, to which NaCl and Na2SO4 were added. The soldered specimen was immersed for 10 days, with sulfate and chloride supplied in increments of 0.01 mol/litre each day. Corrosion current density and HCP were obtained during this addition, and CTV was calculated by graphing the concentrations of sulfate and chloride ions against the corrosive current. Discussions concluded that the presence of chloride and sulfate ions contributes to corrosion, with sulfate ions exacerbating the process due to increased porosity and lack of passivity.

Corrosion studies on super alloys such as superni 718 superni 600 and superco 605 were made and in this study, investigators used the specimen dimension of 20 x 15 x 5 mm sheet [15]. The specimens were abraded using emery paper with grid sizes of 220, 320, 400, 600, and 800, followed by polishing with 0.3 micrometre alumina powder on cloth. Following processing, specimens were positioned in a garbage incinerator operating at 800-1000°C for 1000 hours. Specimens were collected and visually examined, along with weight measurement, after every 100 hours, followed by a 1-hour chilling period in ambient air.

Corrosion products were analyzed using SEM, EDS, and XRD after the testing. Based on the talks, the author concluded that all three alloys demonstrate ash accumulation at the top. Nickel-based superalloy 718 exhibited superior corrosion resistance compared to superalloy 600, attributable to the presence of chromium oxides and nickel chromate, which function as corrosion inhibitors. In the nickel-based specimen, corrosion was seen up to 30 micrometers, however in the Superco 605 specimen, corrosion penetrated around 65 millimeters into the oxide scales, resulting in a high corrosion rate due to the deep infiltration of sulfur along the grain boundaries.

Studies of Corrosion behaviour of duplex and lean duplex stainless steel was done in a pulp mill by experimentation with the samples made of dimensions 1 cm X 1 cm which is obtained in both cold and hot rolled condition [16]. The cyclic potentiodynamic polarization method was employed to compare duplex stainless steel with Lean Duplex stainless steel in white and green liquors, as well as in synthetic liquor. Following the experimental examination of steel characterisation, successful cyclic polarization of DSS and LD SS was conducted in synthetic and industrial white liquor, as well as in green liquor. Cold-rolled steel demonstrates superior physical qualities compared to hot-rolled steel. A polarization curve indicates a reduced potential and elevated current density on DSS in synthetic white liquor relative to industrial white liquor. The authors determined that temperature is the primary factor influencing the corrosion of DSS in white liquor, as the rise in temperature correlates with a reduction in e-trans passive, derived from the average trans passive potential. Additionally, green liquor exhibits a lower trans passive potential, indicating it is a less aggressive medium for DSS.

Reference [17] experimented with IN625 alloy which has been exposed to an automobile racing environment and their response in terms of oxidation and corrosion were studied through various techniques such as atom probe tomography, EDX, SEM and XRD. Initially the IN625 alloy used in the exhaust manifold has been taken, cold rolled and the impurities on the surface were wiped out. Subsequently, annealing was conducted at 1040°C. A block of IN625, measuring 50 mm in length and 40 mm in diameter with a thickness of 1.75 mm, was positioned 100 mm downstream from the engine block. The experimental setup was conducted in a single in-service operation, after which 10 x 10 mm specimens were extracted from the block for all the aforementioned characterizations. Discussions revealed that the inner surface of the exhaust exhibited an oxide layer three to four times thicker, indicating faster oxidation due to exhaust fumes, accompanied by significant contamination from Zn, P, K, and Na. The formations of chromium spinels were same in both the treated and untreated portions of hot exhaust gas. Beneath the oxide scales, both treated and untreated regions have analogous microstructural characteristics, and the in-service condition reveals a uniform presence of delta phase up to 1000°C.

Three specimens measuring 12 x 8 x 1.5 mm were fabricated from 1Cr 18Ni 9Ti stainless steel; one specimen was coated with Al-Si, another with Al/Si-Cr, and the third was left uncoated. All specimens were maintained in a box furnace at 950°C for 24 hours. A graph illustrates weight increase over time during the experiment, then followed by characterisation using SEM techniques. The characterization indicates that the coatings diffused into the matrix at elevated temperatures, serving as a protective barrier against corrosion kinetics. Corrosion kinetics and SEM examination indicate that the Al/Si-Cr coated specimen exhibits two layers (an exterior Cr2O3 layer and a denser inner Al2O3 layer), which provide greater resistance compared to the Al-Si coated specimen, followed by the naked specimen. [18].

Experimental studies about defects in Steel mortar interface and their corrosion behaviour of Steel were made by using EIS, CT along with the characterization techniques such as SEM, EDS [19]. Portland cement, tap water, and river sand were utilized for mortar production in the experiment. A piece of 8 mm diameter reinforcing steel was utilized. This study was conducted using two distinct sorts of circumstances. The initial scenario involved protecting the upper section with epoxy resin to examine varying corrosion behavior, whereas the alternative scenario lacked any epoxy shielding, exposing the casting and conducting electrochemical tests over periods of 10, 60, and 180 days. Six specimens were created for each circumstance in this experiment. Characterization was conducted using FESEM and EDS to examine the corrosion behavior following exposure of the specimens to a 3.5% NaCl solution. The discussion indicates that testing the specimen using non-destructive testing (NDT) revealed corrosion defects on the horizontally oriented steel, particularly in the lower section, attributed to a looser microstructure following exposure to 3.5% NaCl. Characterization methods identified two detrimental effects: the depletion of the calcium hydroxide layer and the diffusion of chloride ions, which compromise the passive film.

Cyclic oxidation and corrosion behaviour of Hastelloy X were experimented by making specimens of dimensions 10 x 10 x 3mm [20]. During the investigation, samples were subjected to temperatures ranging from 900°C to 1000°C for 10 cycles, each lasting 50 hours with a 5-hour soaking period per cycle. The saline environment is created by the mixture of Na2SO4 and NaCl at a ratio of 75% to 25%, respectively. Consequently, the accumulation of salt leads to sulfidation or expedited oxidation of metals. The experimental results indicate a significant mass change at 1000°C compared to 900°C, leading the author to conclude that this is attributable to the effects of electrochemical reactions at elevated temperatures. The distributions of alloying elements were verified using image mapping. Prolonged exposure causes pores to result in the spalling of oxide scales, accompanied by microcracks at 1000°C. In their research, the oxide composition was Cr2O3 at 40.50%, NiO at 28.39%, and Fe at 11%, with tiny traces. Following the removal of the oxide, the composition was Cr2O3 at 39.35%, NiO at 26.83%, and FeO at 34.70%. The oxides are generated as polycrystalline structures due to chemical affinity. Cr2O3 interacts with Fe and Ni to produce spinel nichromite and chromite, which safeguard the substrate against corrosion and oxidation.

Reference [21] investigated the effect of Fe, Ni and Cr on the corrosion behaviour of hypereutectic Al-Si aluminium alloy under various solution temperatures. The engine block was first melted in a clay graphite crucible and subsequently cast into dimensions of 16 x 150 x 300 mm³. Four distinct alloys were then produced by incorporating Fe, Ni, and Cr in specified proportions, resulting in alloys 2, 3, and 4, while alloy 1 served as the master alloy derived from the melted engine block. The alloys were solutionized at 530°C for 2 hours, and samples measuring 55 x 15 x 3 mm³ were fabricated from the alloys. Samples underwent degreasing and polishing. Subsequently, 3.5% NaCl and 96.3% distilled water were used and sustained at increased temperatures. The samples were subsequently weighed and subjected to rotation in a 3.5% NaCl solution for 30 days, for a duration of 8 hours each day. Finally, after reweighing, the gravimetric test yielded the weight gain/loss results. Electric conductivity was employed to determine conductivity, from which resistivity was subsequently computed. Characterization was conducted using SEM and EDX. Discussions to the conclusion that the presence of alloying elements influences corrosion. Initially, intermetallic compounds function as a barrier that exhibits resistance to corrosion and oxidation; however, elevated temperature and velocity result in the degradation of this passive barrier, hence exacerbating corrosion, mostly attributable to NaCl compounds.

Reference [22] investigated the fracture behaviour and effective performance of IN625 by uniaxial tension and cyclic compression. For which predominant tensile strength values in accordance with the strength of the material in order to raise the S-N curve were taken. Micro and macro-structural characterisation was conducted in the areas of fracture propagation, revealing the presence of fatigue striations. To conduct testing, hardening mechanisms were established by the precipitation of MoC or NbC-type carbides and Cr23C6 distributed inside the austenitic structure. The tensile and hardness tests adhered to the ASTM E8M-08 standard, whereas the fatigue test conformed to the ASTM E466-1513 standard for specimen preparation and experimentation, utilizing FESEM and EDS for structural characterization. The fatigue strength of IN625 is 244 MPa for indefinite life, defined as 107 cycles at a loading ratio of R = -1 s. Fracture surface research of IN625 reveals that the first fracture is ductile, characterized by an unstable initiation of the crack, with subsequent failure exhibiting tearing topologies and cleavage regions within a stable growth area. It was shown that a decrease in stress amplitude correlates with an increase in the stable growth area. The IN625 exhibits enhanced mechanical strength and moderate hardness, coupled with ductility, facilitating the examination of fatigue striations, particularly in relation to microstructures, gamma phase, and the presentations of NbC and MoC.

Corrosion studies of IN625 were made in molten nitrate salts which consist of 40 wt. % of kNO3 and 60 wt. % of NaNO3 at 500 and 600℃ [23]. The authors used electrochemical impedance spectroscopy, open circuit potential measurements, gravimetric analysis, and potentiodynamic polarization to assess corrosion behavior and degradation mechanisms. IN625 with dimensions of 26x17x17 mm was utilized in the gravimetric test for investigation. During the electrochemical test, specimens were configured as working electrodes in conjunction with platinum and aluminum tube reference electrodes within a container that was continuously purged with argon gas during the experiment. Subsequent to the experimentation, the outcomes were analyzed by characterisation. The scientists found that the weight loss approach demonstrates that specimens adhere to parabolic law at both temperatures. In a potentiodynamic approach, alloys developed a non-protective coating at the anode, leading to diffusional polarization. In the EIS approach, two loops are generated: the first resulting from corrosion and the second from diffusion. Polarization charts indicate that icorr (corrosion rate) escalates with temperature, resulting in pitting from sodium nitrate at a concentration of 0.1 mol at 600℃. This inhibition results from the adsorption process on the surface of the specimens.

Reference [24] experimented 310 SS material with the corrosive salt environment of Na2SO4+V2O5 750, 900 and 9500C and revealed both hot oxidation and corrosion behaviour of the same. For this experiment, the authors prepared several specimens, each measuring 10 × 10 mm, in accordance with the laboratory specimen preparation protocol. Five specimens were subjected to cyclic thermal stress at about 750, 900, and 950 degrees Celsius. Two specimens were placed at 750°C and 900°C, while one specimen was placed at 950°C. For the corrosion investigation, identical specimen placements were conducted in conjunction with a corrosive salt environment of 2 mg/cm². Weight measured every two hours for a total of fifty hours in both oxidation and corrosion scenarios separately. Subsequently, utilizing SEM, EDS, XRD, and visual examination, corrosion kinetics and elemental analysis were conducted, leading to results. Oxidation resulted in the formation of oxides, leading to weight rise; however, corrosion spallation of the protective layer facilitated the depletion of the subsequent layer, resulting in weight loss. Oxidation produces Cr2O3, which safeguards the underlying layer underneath the scale; nonetheless, elevated temperatures result in scale cracking, and in instances of corrosion, the rate of corrosion escalates exponentially with rising temperatures. Sulphide ions induce material spallation, leading to the subsequent degradation of the underlying layer.

The corrosion behaviour of SS316 DS2205 and CS1008 alloys was studied in 20.5 % NaCl + 73.5 Na2SO4 at 7000C for about 120 hours for thermal energy storage through optical microscopy, electrochemical measurements, SEM, EDS and EBSD techniques [25]. Test coupons measuring 25 x 5 x 1.4 mm were fabricated from all aforementioned alloys and subsequently evaluated using potentiodynamic polarization methods and static corrosion procedures. Test coupons of electrodes for PDP measurements were manufactured according to standards, submerged for one hour in molten salt contained in a crucible, and subsequently analyzed using EIS and PDP measurements. For static measurements, test coupons were submerged halfway into the salt to evaluate both the treated and untreated surfaces of corrosive salts. It is distinctly observable in micrographic analyses. High Cr ions in these alloys generated a negligible protective layer on the surface, as proven by EIS. Among these materials, CS1008 exhibited more susceptibility than the other two due to the substantial iron oxide scale that fails to form a protective layer. SS316, when next to CS1008, is susceptible to corrosive damage from sulfur and chloride ion infiltration, as well as the solubility of the oxide coating, resulting in metal failure. In contrast, DSS2205 exhibits comparable corrosiveness to SS316, but its parallel layers of austenite serve as a barrier to effective oxidation.

Study of corrosion behaviour of type 316L SS was studied with the experimentation with the samples of mill annealed 316L 20 x 20 x 1mm strips [26]. Electrochemical polarization experiments were conducted at ambient temperatures of 500°C, 700°C, and 900°C in 30 wt.%, 40 wt.%, and 50 wt.% aqueous NaOH solutions. Experiments were conducted with a Schlumberger Solectron Potentiostat with a scan rate of 1 mV/s. Maximum critical current density was determined by potentiodynamic tests, while the corrosion rate was assessed using the linear polarization technique at open circuit potential. Weight loss tests were conducted at temperatures ranging from ambient temperature to 900°C during preset durations of 35 days to 4 months. Graphs were constructed using the experimental findings, depicting the relationship between current density (passive) and length (passive) for both aerated and de-aerated conditions. The passive behaviors were analyzed in relation to temperature, de-aeration, NaOH concentration, and surface film development. The authors determined that 316L stainless steel attains a critical corrosion rate of 18 mm/year in de-aerated 50% wt. NaOH, whereas an open circuit potential reveals a corrosion rate of 0.5 m/year in the same environment. At temperatures over 500°C, a black surface coating composed of NiO and Ni(OH) appeared on the surface. Ultimately, the performance of 316L stainless steel in a caustic environment and under de-aeration elevates the corrosion rate, however at room temperature with 30 wt. % NaOH, the outcome is contrary.

Reference [27] experimented a set of 12 different compositions of alloys majorly Fe Cr Al Na concentrations in order to find the critical concentration of Al, Cr-Ni which is used to maintain the austenitic phase during high temperature. Samples were created using the aforementioned 12 distinct combinations of Fe, Cr, Al, and Na model alloys, with a diameter of 10 mm and a thickness of 1.5 mm, with a central hole of 1.5 mm in diameter. Subsequently, all specimens were subjected to corrosion resistance testing at temperatures of 550°C and 650°C for 1000 hours in molten lead with an oxygen weight percentage of 10^-6, as this study primarily focused on the domain of high-temperature liquid metal energy storage and conversion. The analysis and findings were derived from characterisation techniques including SEM, EDS, and XRD. According to the findings, six out of twelve compositions exhibit superior corrosion resistance at both 550 and 650°C over a duration of 1000 hours, indicating the essential concentrations of Al and Cr-Ni that sustain the austenitic phase by facilitating the formation of passivating scales Al2O3 and Cr2O3, specifically Fe (20-29), (15.2 to 16.5) Cr, and (2.3 to 4.3) Al. A transition layer composed of an intermetallic matrix of nickel and iron was generated underneath the oxide scale after temperature exposure. Furthermore, the authors determined that a rise in alumina, accompanied by a decrease in chromium content, stabilizes the austenitic phase and inhibits the formation of the ferritic phase; hence, these critical concentrations enhance corrosion resistance.

An experiment was made to study the effect of surface modification on the hot corrosion resistance of IN718 at 700℃ by aluminizing and USSP process [28]. A specimen of IN718 with a diameter of approximately 10 mm is subjected to peak aging treatment. A high-activity aluminizing process was subsequently conducted in a single step by immersing a predetermined alumina powder combination in an alumina crucible. A separate specimen of IN718 is subjected to shot peening by USSP using stress voyager (SONATS) apparatus. Samples underwent shot peening using 3 mm diameter C6 grade steel balls for 5 minutes at a consistent amplitude of 80 micrometers. Experiments were conducted in two distinct environments: one consisting of a 100 wt. % NaCl mixture and the other comprising a mixture of aluminum powder, NH4Cl, and Al2O3 powder in a furnace at 700°C. Following characterization and analysis, the authors concluded that the USSP process enhances surface reactivity, resulting in significant corrosion of the bare specimen. The aluminized specimen exhibits a 50% decrease in corrosiveness, attributed to the barrier layer of aluminum oxide, with sodium chloride demonstrating more aggressiveness in comparison to two environments.

Hot corrosion study of T22 boiler Steel was made at 900℃ on four different Cr3Cr2 NiCrcoatings [29]. The substrate base metal T22 steel for this investigation consists of samples measuring 20 x 15 x 5 mm³. Subsequent laboratory techniques for specimen preparation, including varied grit sheet polishing and washing, were performed. Four distinct quantities of Cr3Cr2 NiCr, namely 35/65, 20/80, 10/90, and 0/100, were utilized in powder form and subsequently sprayed employing the HVOF process. Subsequently, utilizing a silicone tube furnace, the hot corrosion behavior of the samples was assessed by preheating them to 250°C before to the application of a Na2SO4-60% V2O5 salt mixture. The experiment was conducted for 50 cycles of thermal cyclic loading at 900°C, utilizing SEM, EDX, and XRD characterisation, along with a corrosion analysis. The authors observed that 100 NiC specimens exhibit superior corrosion resistance with less weight loss compared to those subjected to a 90% NaCl solution in an 80% NiCr combination. The uncoated specimen exhibited spalling and significant weight loss, indicating severe corrosion.

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| **Table 1:** Based on the review of all research works, an overview is listed here, |
| **Author** | **Materials** | **Methodology** | **Techniques/Characterization** | **Observations** |
| (Kamal et al., 2010) | superni 75, superni 718 and superni 800H | Thermal Cyclic loading | FESEM, EDAX, X ray mapping and weight gain/loss analysis | superni 75 exhibits better resistance |
| (Güneyisi et al., 2013) | 16 mm steel bars | Reinforcing steel bars with 5 % and 15 % Meta kaolin as binders and then testing at accelerated corrosion. | Accelerated corrosion, Electro-chemical Test, Current density – LPR, corrosion rate by CPR  | 15 % weight of meta kaolin added specimens provides longest time to failure with 50 % reduction to corrosion rate |
| (Mirshekari et al., 2014) | 304L SS | Corrosion study on weld passes on specimen by potential dynamic polarization and emission test | optical microscopy, SEM, EDX, XRD and hardness is measured by Vickers hardness | Number of welds passes increases, corrosion resistance increases. |
| (Yan et al., 2013) | alumina forming austenitic stainless steel by re-melting and casting, nickel based super alloys K438 and 417 | Thermal Cyclic loading | SEM, EDS and XRD | Protective scales of Aluminium oxide and chromium oxide scale formed during oxidations acting as a barrier to the corrosion.  |
| (VADAYAR & RANI, 2020) | IN738 LC and CM 247 LC | Thermal cycling of 7000C and 9000C | Scanning electron microscopy and EDS, weight gain /loss method | CM 247 LC resist corrosion then IN 738 LC |
| (Mahobia et al., 2013) | super alloy IN718 | 3 mixtures of Na2SO4 NaCl and vanadium oxide on the specimen prepared and tested under thermal cycling | Scanning electron microscopy and EDS, weight gain /loss method | 90 wt. % of Na2SO4 5% NaCl and a 5% vanadium oxide coated specimen gives better corrosion resistance. |
| (López et al., 2014) | low alloy ferritic steel with Ni-50 Cr coatings | Thermal cyclic loading at two different temperatures with three levels of carbon di0oxide volume. | x-ray diffraction, SEM, light microscopy (image analysis) | coated substrate does not show any cracks as uncoated. |
| (Solecka et al., 2016) | IN625 and IN686 | Boiler pipes made of 16MO3 Steel where cut and coated with IN625 and IN686 and then expose 6500C for 1000 hours in waste incineration ashes. | SEM, EDS and XRD | IN625 makes thin film of NiO and Cr2O3 and Cr2O2 protect the material from harmful ashes |
| (Retschitzegger et al., 2016) | 13 Cr Mo (4-5), P91 (1.49) and P91 (1.45) | Thermal loading on biomass fixed grate furnace at two different temperatures, two different fuel and two phases. | probe methodology to obtain corrosion data for measurement error | P91 (1.45) shows better corrosion resistance and 13 Cr Mo (4-5) was at low temperature |
| (Niu & Nakada, 2015) | 13 Cr Steel | Pitting corrosion study by Electrochemical corrosion test with test water of three proportions and specimens as electrode. | potential dynamic, potentio-static and pit growth behaviour | test water with 50 PPM sulphide suppresses pit growth. |
| (M. Kumar et al., 2015) | SAE213 T22 and SAE516 grade 70 Steel | Thermal cyclic loading at elevated temperature for 15 cycles for erosion-corrosion study by cold spraying of **Ni-20Cr** | SEM, EDX and XRD | Coated specimens exhibit improved hardness with better erosion corrosion resistance |
| (Ramkumar et al., 2017) | IN625 and IN78 | Dissimilar welds with different filler rods and then cyclic hot corrosion test 50 cycles in molten salts | metallurgical study | IN625 with ErNiCrMo-4 filler rod gives better corrosion resistance |
| (Patel et al., 2016) | Various materials on each research paper | 111 Research papers were reviewed by the author | mostly through gravimetric SEM, EIS, potentiodynamic polarization and OCD | proper research with experimental study can lead to a new alloy which is compatible to the harsh corrosive environment |
| (Liu et al., 2016) | Steel used in concrete | Prepared specimens were gone for electrochemical test and predetermined adding of chloride and sulphate ion for corrosion study | EIS, OCP, LPT and CTV | presence of chloride and sulphate ions leads to corrosion |
| (Mudgal et al., 2016) | superni 718 superni 600 and superco 605 | Thermal cyclic loading in actual waste incinerator | SEM, EDS and XRD | Nickel based superni 718 showed better corrosion resistance followed by superni 600 |
| (Esteves et al., 2018) | duplex and lean duplex stainless steel | Cyclic potentiodynamic polarization | effective cyclic polarization of DSS and LD SS in synthetic and industrial white liquor and then green liquor | temperature is the key parameter of DSS corrosion in industrial white liquor rather than green liquor |
| (Pedrazzini et al., 2018) | IN625 alloy | Exposing the selected material to automotive racing environment by placing it downstream the engine block in predetermined time and followed by characterization | tom probe tomography, EDX, SEM and XRD | the inner surface of exhaust had three to four times of oxide layer which shows accelerated oxidation, both the treated and untreated areas exhibit similar micro structural features and also in-service state shows consistent form of delta phase up to 10000C |
| (Fu et al., 2017) | 3 specimens of 1Cr 18Ni 9Ti SS and one is coated with **Al-Si** and another one is with **Al/Si-Cr** and the third one is kept as bare specimen | Thermal loading at box type furnace at 9500C for 24 hours followed by corrosion study | corrosion kinetics along with the SEM analysis | **Al/Si-Cr** coated specimen shows more resistive action than Al-Si coated specimen |
| (J. Shi & Ming, 2017) | Steel mortar interface | Two scenarios of steel mortar (with & without shielding of epoxy) and exposing it to corrosive environment and then study by EIS, CT | FESEM and EDS | corrosion behaviour was seen on the horizontal oriented steel due to depletion of calcium hydroxide layer and also diffusion of chloride ions which destroys the passive film |
| (Chellaganesh et al., 2018) | Hastelloy X | Thermal cyclic loading at elevated temperature in corrosive salt environment for 10 cycles followed by characterization studies. | Image mapping, corrosion kinetics, SEM | Cr2O3 reacts with Fe and Ni to form spinal nichromite and chromite which protects the base from corrosion and oxidation |
| (Kaiser et al., 2018) | hypereutectic Al-Si aluminium alloy | Four different alloys were made and rotated in NaCl and followed by weight gain/loss and characterization | gravimetric test, weight gain/loss, SEM, EDX | alloying elements have effect on corrosion, Initially, intermetallic compounds act as a barrier then at increasing temperature, corrosion increases. |
| (Lima Pereira et al., 2018) | IN625 | Hardening mechanism followed by mechanical test for testing fracture behaviour & performance | FESEM and EDS. | On microstructure study, Nbc and MoC presence, the IN625 provides better mechanical strength and medium hardness to ductility |
| (Khorsand et al., 2018) | IN625 | Corrosion study on selected material with salt coating and experimental study by various techniques | electrochemical impedance spectroscopy, OCP, gravimetric test, potentiodynamic polarization | specimens obey parabolic law through weight gainloss and increase in temperature lead to corrosion |
| (Shaikh et al., 2018) | 310 SS | Thermal cyclic loading at four different temperature in two different salt environments | SEM, EDS, XRD and visual inspection, corrosion kinetics and elemental analysis | During oxidation, Cr2O3 formed which protects layer beneath the scale and rise in temperature leads to cracking. |
| (Sarvghad et al., 2018) | SS316, DS2205 and CS1008 alloys | Opted material is tested for corrosion behaviour through thermal energy storage with salt environment followed by its study | optical microscopy, electrochemical measurements, SEM, EDS and EBSD techniques | SS316 and DS2205 shows similar behaviour and CS1008 were found to suffer more. |
| (Davalos Monteiro et al., 2020) | 316L SS | Weight loss experiments, Experiment with Schlumberger Solectron Potentiostat  | Electro chemical polarization test, open circuit potential | Material shows different behaviour in varying weight % of NaOH environments |
| (H. Shi et al., 2019) | set of 12 different composition of alloys | Samples, combinations of Fe Cr Al Na model alloys were prepared and maintained at austenitic phase for 1000 hours in molten lead | SEM, EDS and XRD | increase in alumina with decreasing chromium content fixes austenitic phase |
| (S. Kumar et al., 2019) | IN718 | Thermal loading by making two different specimens of two different methods by salt and crucible coating for elevated temperature in furnace  | SEM, EDS and XRD | Aluminized specimen makes 50% reduction in corrosiveness |
| (Singh et al., 2019) | T22 boiler Steel | Substrate is coated with Cr3Cr2 NiCr with four different proportions and tested by thermal loading | SEM, EDX and XRD | 100 NiC are specimen provides better resistance to corrosion with low weight loss |

**6. Conclusion**

Based on these different research works with various techniques utilized to study the corrosion behaviour and its characteristics,

The materials employed, including SS310, 304L SS, IN625, IN718, Superni 75, and Superni 78, include a high nickel content, are rich in chromium, and contain a significant amount of aluminum, which enhances corrosion resistance by generating chromium oxides during oxidation. These oxide scales safeguard the substrate from corrosion and degradation of the base material. Among these materials, SS310, 304L SS, and SS316 demonstrate lower costs in comparison to nickel-rich superalloys.

Various experimental procedures are conducted in the aforementioned research works for this review, including open circuit potential, electrochemical testing, electrochemical impedance spectroscopy, weight gain/loss method, potentiodynamic polarization, thermal cyclic loading at elevated temperatures, and potential dynamic polarization. Most research studies employed thermal cyclic loading at extreme temperatures and utilized weight gain/loss methodologies to investigate corrosion behaviour. The alternative experimental procedures necessitate supplementary efforts and equipment, resulting in increased energy consumption, costs, and time requirements.

The characterisation investigation of corrosion will likely include FESEM, EDS, XRD, image mapping, corrosion dynamics, gravimetric tests, and optical microscopy. Each investigation employs a distinct characterisation process with specialized equipment. The corrosion behavior, rust proliferation, and material degradation may be assessed to diagnose substrate longevity. The approaches enable the examination of microstructures, elemental composition, and elemental behaviour in applications, hence facilitating the creation of alloy compositions through surface modification and heat treatments.

Material selection should be based on available resources to minimize extraction labor, costs, and time. The selection of processes, followed by experimental research or investigation, must be cost-effective for substantial capital expenditures and investments. These straightforward methods will facilitate optimization through novel alloying and comprehensive characterisation, addressing not only environmental and social considerations but also the health implications for the workforce.

This review concludes that investigating the corrosion behaviour of high-temperature materials through surface modification and weight gain/loss methods, in conjunction with electrochemical impedance spectroscopy, is advisable for a more comprehensive understanding of material functions and their modifications.

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