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Metal corrosion in high temperature conditions: A review

ABSTRACT

This work reviewed previous studies relevant to the mechanisms of metal corrosion in extremely high temperatures, the combined effects of pressure and chemical species on corrosion processes, and the development of innovative materials and coatings made to withstand these challenging conditions. The complex interactions between temperature, pressure, and chemical species were highlighted in the investigation as factors that accelerate corrosion rates of metals in a variety of industrial environments. Data from numerous experimental studies and industrial applications were analyzed as part of a thorough literature review conducted for the research. Previous studies reported that corrosion mechanisms, including fluxing, hot corrosion, sulphidation, and corrosion fatigue, including protective oxide scales were found to be crucial in maintaining material integrity. New materials designed for extreme temperature resistance, such as high entropy alloys, high-temperature metallic glasses, and oxide-dispersion-strengthened alloys, were reported to show superior strength, oxidation resistance, and creep performance including protective coatings, like vitreous ceramic-like enamels and phase composite ceramic thermal barriers. To improve the durability and performance of metals in extreme environments, the research highlighted the significance of material composition, coating microstructure, and application techniques in determining the effectiveness of corrosion protection methods. Based on these findings, the study recommended additional research into the development and optimization of advanced materials and coatings for particular high-temperature applications, as well as the integration of these solutions into industrial processes.

Keywords: *high-temperature corrosion, oxidation, protective coating, non-protective coating, novel materials for extreme environments*

1. INTRODUCTION

The breakdown of materials under difficult circumstances, such as high temperatures, chemically aggressive solutions, and biologically active surroundings, is known as corrosion in extreme environments. Researching the processes of deterioration and creating materials resistant to corrosion are difficult in these conditions [1,2]. For example, metallic zirconium may oxidize due to high-temperature steam, underscoring the need of comprehending corrosion processes in nuclear cladding alloys [3]. According to Young et al. [4], failure mechanisms for microbiologically influenced corrosion (MIC) are contingent upon the interplay between the environment, microbes, and metal characteristics. MIC can transpire in a variety of conditions. In harsh maritime environments, materials such as austenitic stainless steel and unalloyed ductile iron corrode at different rates and exhibit microstructural changes over time. The menace of corrosion is massive, especially when left unchecked and previous studies have been conducted to prevent the corrosion of steel in various acidic environments [5–15]. Studies have also been done to probe the corrosion of weldments in different study environments [16,17], but extensive research is necessary for the optimal design of corrosion-resistant alloys because corrosion in extreme conditions can hasten material loss.

Extreme temperature environments can cause a variety of corrosion processes in metals.

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Sulphidation and hot corrosion are examples of high temperature corrosion that can occur above 400°C in the absence of liquid water [18]. Studying alloy behaviour in oxidizing environments is necessary for grasping high-temperature corrosion processes [19]. In harsh environments, austenitic stainless steels and nickel-based alloys can form protective passive films that enhance corrosion resistance up to a certain temperature [20]. Heat treatment operations can significantly affect the corrosion vulnerability of duplex stainless steel, changing its passive film stability and increasing corrosion rates [21]. The composition of alloys, with particular components such as chromium, silicon, and molybdenum impacting sulphidation and carburization resistance, is critical in determining corrosion resistance in circumstances with high sulphur and carbon potentials [22].

The corrosion of metals in high-temperature conditions is an important field of research for many industries. Studies on corrosion mechanisms have been conducted in high-temperature conditions such as molten salts, where the interactions between metals and salts result in distinct paths for morphological evolution [23]. Furthermore, it has been noted that the use of carbon fiber reinforced polymers (CFRP) on steel in harsh weather has the potential to improve mechanical qualities; nevertheless, there is a worry regarding the possibility of localized corrosion, such as pitting [24].

The rate at which metal corrodes may be greatly impacted by extreme heat. The corrosion vulnerability of 2101 duplex stainless steel rises when exposed to temperatures above 1200°C. Aggressive conditions such as solutions containing 2 M H2SO4 and 0%–1.75% NaCl exhibit the highest corrosion rates [21]. Similar to this, generalized and pitting corrosion is caused by superheated steam that causes condensation on carbon steel and 13% Cr stainless steel. The corrosion process is regulated by the concentration of chloride in the steam [25]. Moreover, the rate of corrosion was found to be inversely proportional to the deposited oxide thickness in a study on 9Cr-1Mo ferritic steel exposed to high heat fluxes, suggesting a diffusion-controlled reaction influenced by water molecule diffusion through the oxide layer [26]. In essence, high temperatures change the surface properties and metallurgical structure of metals, hastening the corrosion process in various conditions.

It is imperative for industries like as aerospace and power generation to comprehend the causes of corrosion at severe temperatures [18,27]. Most of the research focuses on moderate temperature ranges, but complete information about the behavior of materials in severe circumstances is lacking [28,29]. In harsh applications, high-temperature corrosion processes that affect nickel-based superalloy performance include Sulphidation, hot corrosion, and corrosion fatigue [30]. However, very low temperatures can be problematic for electronic dependability, particularly in deep space travel where solder junctions are impacted by low-temperature brittleness. A thorough grasp of oxidation-induced deterioration and the concurrent optimization of mechanical qualities and corrosion resistance are necessary for the development of materials resistant to severe temperatures. This information may help develop stronger coatings and materials for use in challenging conditions.

Promising advances in materials and coatings for hostile environments have been made, such as the development of multi-principal-component ceramics for use in extreme conditions as lasting thermal barrier coatings (TBCs) [31]. PVD methods have also been applied to produce hard and wear-resistant coatings, with an emphasis on composition optimization and microstructural tailoring to improve tribological qualities [32]. Additionally, utilizing finite element modeling to study the impact resistance of automobile coatings has shown how crucial primer mechanical qualities are to enhancing durability and safety [33]. Oxide-based and nitride coatings, among other corrosion- and wear-protective coatings, have been emphasized as useful methods for guaranteeing the durability and long-term performance of materials in harsh environments [34].

To improve durability and safety, it is essential to investigate new materials and coatings designed for harsh situations. Research in this field has shown encouraging results, including the development of multi-principal-component ceramics [35] and high-entropy alloys (HEAs) [36]. For example, because of their special microstructural characteristics and intricate composition, HEAs provide remarkable resistance to wear, corrosion, and oxidation. Furthermore, innovative production methods such as laser-based additive manufacturing have made it possible to produce alloys that are strengthened by oxide dispersion and have better mechanical strength and resistance to oxidation [37].

This work aims to review:

i. Previous studies on corrosion mechanisms in extreme conditions,
ii. The synergistic impact of pressure, and chemical species on metals at elevated temperature, and

iii. Evaluate novel materials and coatings that with stand metal corrosion at high temperatures.

2. HIGH TEMPERATURE OXIDATION

The oxidation of metals at high temperatures is a major problem because it affects material lifetimes and requires efficient corrosion protection techniques [4,38,39]. To address these practical issues, it is important to understand the rate of oxidation and control the reaction's morphology. Research has examined the oxidation behavior of different metals, taking into account factors like grain size, crystal structures, and diffusion mechanisms that affect the oxidation process [40]. Furthermore, research has shown how crucial it is to create new alloying ideas and alter production processes in order to improve high-temperature oxidation resistance [39]. In order to control oxidation-induced degradation and prolong material lifetimes, it is crucial to have a basic understanding of the underlying processes and the capacity to modify them, which emphasizes the significance of integrating experimental and computational methods for precise lifetime predictions and material selection [30].

Materials' ability to withstand oxidation is largely determined by the creation of an oxide scale, and the scale's ability to stick to the substrate is critical in stopping more oxidation [41–43]. The ratio of oxide to oxidized metal volumes is known as the Pilling-Bedworth Ratio (PBR), and it is a crucial metric for predicting the protective qualities of the oxide layer [44]. When the PBR is less than one, it means that the oxide covering is not protective; when the PBR is much higher, more than 1.8, it means that the oxide thickness is too thick and can trigger mechanical stresses in the layer that may result in oxide rupture [41].

2.1 Non-protective oxides

The oxidation process proceeds at a steady pace until a metal creates an oxide with a Pilling-Bedworth Ratio of less than one, which results in non-protective oxides. In this case, the oxidation kinetics and the properties of the produced oxide scale may be used to calculate the metal thickness loss or x. Studies have indicated that the kind of oxide scale is a major factor in the metal's ability to withstand corrosion, with various oxide compositions demonstrating differing degrees of corrosion protection [20,45]. The metal's thickness loss, x_L, may be computed using the oxidation kinetics and the characteristics of the produced oxide layer as follows [20]:

$$x_L = C_J t_m \qquad \text{....(1)}$$

where,

C_J = the metal's constant and t_m represents the time.

Environmental factors, alloy composition, the presence of foreign materials such as carbides or oxide particles, and the composition of the oxidant atmosphere and the presence of water vapor are important factors that affect both the rate of oxidation and the oxide layer's morphology [46,47]. In addition, the thickness loss of the metal during prolonged exposure to hot gas can be affected by the emergence of an oxidation barrier with a scattering length density lower than that of the metal [48].

Furthermore, the stability and catalytic activities of metal oxides are strongly influenced by their structural characteristics, such as porosity and crystallinity, underscoring the significance of oxide structure in influencing the material's overall performance [49]. Moreover, research has shown that sophisticated methods such as X-ray Raman scattering may be used to identify and measure certain characteristics of metal oxides, offering important information on their composition and physical characteristics [50]. Furthermore, studies on the oxidation kinetics of different metal films have shown that the work function of the metal affects the development rate of oxides, suggesting a direct relationship between oxide formation rates and metal characteristics [51].

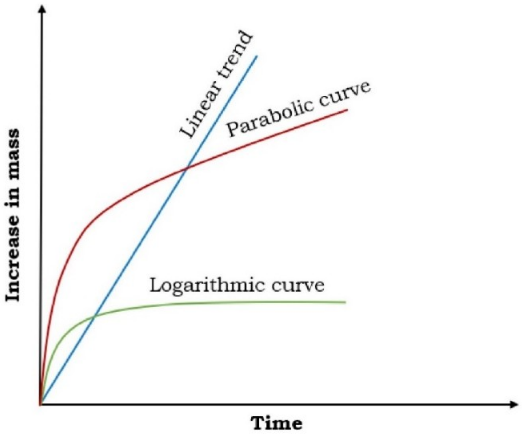

Figure 1. *Kinetic pattern of samples' mass change during hot corrosion* [20]

Depending on the material and environment, the thickness of non-protective oxide and time might have different relationships. Huneycutt et al. (2017)'s research on the oxidation kinetics of ferritic steels demonstrates that, once steady-state conditions are met, oxide thickness grows linearly with time before changing to a parabolic relationship [52]. A linear relationship was shown by [20] as indicated in Figure 1. Furthermore, Niranatlumpong et al. investigated the oxidation behavior of Ni–Cr–Al–Y coatings and observed that, after extended exposure, subparabolic behavior might arise from the depletion of aluminum in the coating, which would result in chemical failure and the creation of distinct oxide layers [53]. Thus, even while certain oxide growth behaviors could initially show a linear connection, several variables, including the composition of the material and exposure circumstances, might affect the long-term behavior.

Different processes cause molybdenum (Mo) and magnesium (Mg) to display non-protective oxide behavior at increasing temperatures. Because of the high reactivity of magnesium to oxygen, it oxidizes and grows MgO lamellae and dendrites, which in turn degrades structurally [54]. However, the oxide of molybdenum, MoO_3, is volatile, having a melting point of 795 °C and a boiling point of 1100 °C. This means that oxidation is increased by sublimation, and throughout the oxidation process, a porous silica structure is formed [55]. The two metals illustrate the difficulties presented by their oxides at high temperatures: magnesium exhibits bulk atom outward diffusion, while molybdenum's volatile oxide influences both its structural development and oxidation kinetics.

2.2 Protective oxides

Two different trends—parabolic and logarithmic—are shown in the corrosion rate reduction with time when an oxide is protective (see Figure 1), as indicated by a Pilling-Bedworth Ratio (PBR) greater than one [34,56]. The capacity of protective oxides, such as Nd_2O_3 and Y_2O_3, to lower the corrosion rate of the magnesium matrix is shown by PBR values over one, which are obtained from certain precipitated phases in magnesium alloys [56]. Furthermore, oxide-based coatings like titania (TiO_2), yttria (Y_2O_3), and alumina (Al_2O_3) are said to offer improved wear and corrosion resistance, which is consistent with the idea of protective oxides having PBR values greater than one [34]. With the corrosion rate declining either parabolically or logarithmically over time, these protective oxides develop a barrier that slows down the corrosion process and demonstrates how successful they are in maintaining the integrity of the underlying material. This behaviour can by represented by the relationships [20].

$$x_L = CJ_2\sqrt{t_m} \qquad \ldots\ldots(2)$$

$$x_L = CJ_2 \ln\left(CJ_4 t_m + 1\right) \qquad \ldots\ldots(3)$$

Where t_m is the time and CJ_2, CJ_3, and CJ_4 are metal-related constants.

Metals such as aluminum and chromium deviate from parabolic oxidation kinetics due to slower ion diffusion rates in zinc and chromium and poor electron mobility in aluminum and beryllium [57,58]. Because of their similar crystalline structures to the underlying metal, aluminum and chromium oxides develop protective coatings that provide adhesion and shielding [57]. When oxygen ion transport is sluggish, the oxidation rate becomes parabolic and grows at a rate proportionate to the ion flux, which is controlled by Fick's law [57]. The thickness loss during extended exposure periods may be predicted by looking at the oxidation rate constants (CJ_2) for metals at 1000 °C; values for Fe, Cr, and Al have been provided [57]. Because of the temperature-dependent diffusion coefficient, the oxidation rate and temperature have an Arrhenius-type correlation where the growth rate rises with temperature [57].

$$R_2 = R_2 e^{-\frac{E}{kT}} \qquad \ldots(4)$$

where,
R_2 = at a reference temperature, R_2 is constant.
R = the gas constant.
T is the temperature.
E = Energy of activation.

Comparing the electrochemical mechanisms of hot and aqueous corrosion with an emphasis on electron and ion transport shows different processes. Whereas hot corrosion is a chemical process affected by gas-phase kinetics, aqueous corrosion is a result of electrochemical reactions fueled by the presence of a liquid water phase [20]. Ionic diffusion and electrical conductivity inside the oxide are factors that impact the formation of an oxide layer in hot corrosion, which is the chemical deterioration of a metal exposed to hot gasses exceeding 400°C [20]. The oxide layer offers both ionic and electronic conductivity, with the oxide surface acting as the cathode in contact with the environment. The metal serves as the anode in this system [20]. Comprehending these processes is essential for anticipating and minimizing corrosion in situations with elevated temperatures, as those found in engines of aircraft [59].

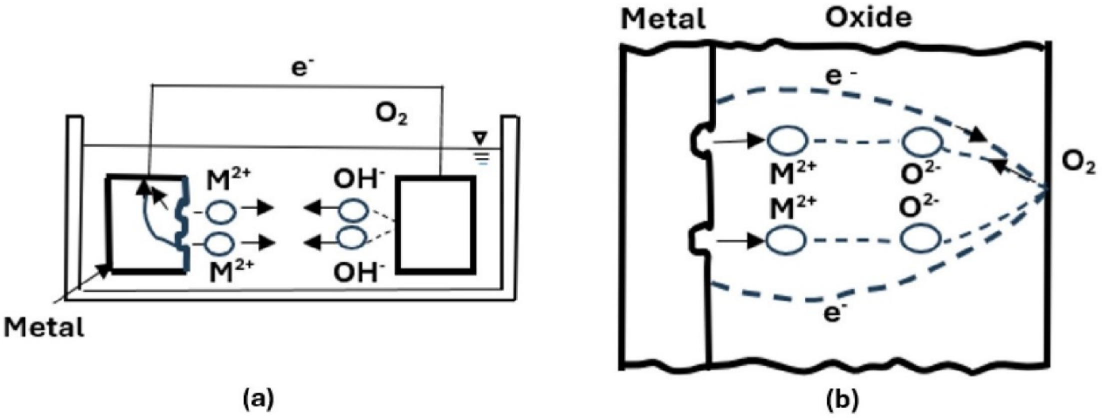

Figure 2. *Comparison of the mechanisms of corrosion: (a) aqueous corrosion; (b) hot corrosion [20,60]*

The ways in which protective coatings resist heat and aqueous corrosion vary according to their composition and structure. Coatings such as NiCoCrAlY and NiCrAlYTa show improved resistance in hot corrosion conditions by preventing internal sulphidation and producing protective oxides, which lowers the corrosion rate [61]. On the other hand, coatings like TiN and TiAlN perform differently in aqueous corrosion conditions. Thick TiAlN coatings, for example, show better resistance because they form protective Al_2O_3 corrosion products, whereas TiN and thin TiAlN coatings show poor resistance because they form non-protective TiO_2 and sodium salt products [62]. Moreover, the hot corrosion resistance of coatings can be affected by their microstructural characteristics, such as the vertical fissures seen in TBC systems [63].

2.3 Hot corrosion

The term "hot corrosion of metals" describes how metal components corrode more quickly in high-temperature surroundings when they come into contact with corrosive substances such as chlorine, alkali metal vapour, and sulphur compounds. Activated Al_2O_3 has been used to remove alkali metal vapour from hot gas [64], metal oxide sorbents have been used for hot gas desulphurization [65], and changing the composition of paper cups has been studied to prevent the release of contaminants into hot beverages [66]. Moreover, research has demonstrated the significance of hot-stage slag processing in improving the functional characteristics of cooled slag while avoiding metallurgical process interference [67].

There are several processes involved in hot corrosion, a chemical process that happens at high temperatures without the presence of liquid water. In addition to erosion-corrosion aided by solid particles, localized attack at grain boundaries, embrittlement, and the production of non-protective scales, corrosion products, and the loss of metal are some of these mechanisms [59]. In aviation engines, hot corrosion can cause surface deterioration and shorter component lives; this is especially true for parts like the low-pressure turbine stage [20]. Variations in grain size have a major impact on the corrosion behavior of nickel-based superalloy components, causing a shift from pitting to uniform corrosion [68,69]. Exposure to high-temperature corrosive conditions forms $NiCr_2O_4$, Al_2O_3, and sulphides, which make up the makeup of the corrosion layer [70]. Grain coarsening improves corrosion resistance by lowering grain boundary areas, which has an effect on the mechanical characteristics and corrosion resistance of magnesium alloys [71]. Furthermore, in pure iron samples, recrystallization texture has a major influence on corrosion behavior, causing the corrosion resistance to decrease with decreasing grain size [72]. The kinetics of the cathodic hydrogen evolution reaction play a critical role in this process.

Hot corrosion basically happens at the solid-gas interface. Because molten salts are so highly corrosive, their presence doubles the rate of corrosion at comparable temperatures and circumstances compared to high temperature corrosion [73]. They either chemically react with the oxide layers or function as solvents, hindering the formation of a stable oxide. The salts have the potential to degrade the protective oxide layers as they pass through. There are two varieties of hot corrosion: Type I and Type II. Transporting sulphur from a sulphur deposit (a molten salt) through an existing oxide layer is known as type I hot corrosion. Here, it combines with chromium to produce stable sulfides. Chromium eventually completely combines with sulfur and is unable to pass through the oxide layer to shield the body from oxidative damage. The temperature range for type I hot corrosion is 750–950 °C [73]. Type II hot corrosion, which involves base-metal sulfates and needs a certain amount of sulfur trioxide to stabilize, happens between 600 and 850 °C. According to Popov [73], these sulfates obstruct the production of protective oxide layers by reacting with alkali metals to create salts with low melting points. Numerous investigations have shown that the Type II hot corrosion process is a solid-phase mechanism in which fine sulfides and oxides precipitate cooperatively along the corrosion front. The concept of a solid-phase corrosion process was supported by the discovery that the majority of the corrosion products in the pits were nanosized sulfides and oxides [74]. Furthermore, a combination of nanosized sulfides and oxides was seen along the corrosion fronts of Type II corrosion pits, suggesting a solid-phase corrosion propagation mechanism [75]. Experimental findings on a superalloy used in powder metallurgy revealed that different oxides and sulfides made up the corrosion layers, validating the combined mechanism of oxidation and sulfuration in molten sulfate salts [76].

3 CORROSION MECHANISMS, SYNERGISTIC IMPACT OF PRESSURE, CHEMICAL SPECIES ON METALS AND NOVEL MATERIALS AND COATINGS FOR CORROSION PROTECTION AT ELEVATED TEMPERATURES

3.1The mechanisms by which metals corrode in high temperature conditions

Numerous mechanisms that can degrade materials in harsh conditions are part of high temperature corrosion mechanisms. According to Sarkar [77], these processes encompass Sulphidation, fluxing techniques, hot corrosion of types I and II (as explained in section 2.3), and fatigue due to high temperature corrosion. Protection oxide scales, including Cr_2O_3 and $MnCr_2O_4$, have been demonstrated via research to be essential in protecting materials from corrosive conditions [78,79]. Furthermore, research on the relationship between hot corrosive medium and cyclic loading has shown unique micro-mechanisms for type I and type II hot corrosion, which have different effects on fatigue life and failure modes. Research on alloy weldments shows that by encouraging the formation of protective oxides like Cr_2O_3 and $NiCr_2O_4$, which reduce the effects of hot corrosion, methods like pulsed current gas tungsten arc welding (PCGTAW) with particular filler wires can improve corrosion resistance [24]. Additionally, studies on Cr_3C_2NiCr coatings sprayed by HVOF show intact oxide scales and decreased weight increases, suggesting that hot corrosion on boiler steels may be successfully mitigated [80]. In challenging industrial conditions, the significance of material selection, manufacturing methods, and protective coatings in addressing high temperature corrosion concerns have been reported [81]. The summary of results of different findings by different authors is presented in Table 1.

The contact with slags accelerates surface corrosion and leaching in refractories at increased temperatures, which causes fractures to initiate, propagate, and dissolve [77]. The process of corrosion entails the creation of glassy and interacting ceramic phases that promote leaching and dissolution, especially when slags are present [77]. Research conducted on alumina-spinel refractories demonstrates that slags penetrate the microstructure, leading to substantial degradation and the emergence of novel phases such as gehlenite and calcium dialuminate [95]. Furthermore, when slag is eroded by various pH solutions, the ion release and microstructure changes demonstrate that the pH value affects the dissolving process, with alkaline solutions causing slower dissolution but easier suspension and gel formation [96]. In addition, the form of the corrosion profile on the solid surface of refractories in melts is influenced by surface tension, viscosity, and wetting angle [97]. In essence, research on quasi-volcanic corrosion at the interface between MgO-containing $CaO–Al2O_3–SiO_2$ slags and alumina refractory ceramics emphasizes the impact of slag structures on corrosion peaks and processes, with reactive radicals being a major player in the corrosion process [98].

The findings of research conducted by Wei Chen et al. [85]and in 2017 by Nicolas Larché et al. [99] lend credence to the idea that alloys, like Ti2AlNb-based alloys, are more vulnerable to chloride corrosion when exposed to high temperatures and salt spray. It was discovered that under high temperature salt spray conditions, the rapid volatilization of chloride inside oxide layers causes significant damage to the alloy surface. On the other hand, Larché et al. [99] emphasized the synergetic effect of residual chlorine content and temperature on the risk of localized corrosion in stainless steels. Moreover, Surya et al. [100] showed that ceramic coatings, such as alumina-titania, can greatly improve the corrosion behavior of stainless steel at elevated temperatures.

Depending on the circumstances, different metals corrode in different ways in high temperature situations. Intergranular corrosion and

Table 1. *An overview of previous studies on mechanisms by which metals corrode at high temperatures*

Metal/Material used for the study	Temperature of study	Corrosion test method/ Corrosive medium	Mechanism of corrosion	Key findings	REF
P91 and H800 steels CoCrAlYTaCSi, NiCoCrAlY, NiCoCrAlTaReY, NiCoCrAlYHfSi coatings	800 °C under cyclic conditions (1 h heating, 20 min cooling)	WL/25% NaCl & 75% Na_2SO_4	Lateral attack through substrate material below coatings. Corrosion mechanism similar for all evaluated coatings.	CoCrAlYTaCSi coating showed best corrosion resistance among evaluated coatings. All coatings outperformed reference P91 and H800 steels in environment.	[82]
Stainless steel Investigated for corrosion by urea at high temperature	Reducing atmospheres with HCl and varying H_2S concentrations Temperature range between 420°C and 680°C	-	Uniform corrosion underneath deposits are main driver.	High temperature decomposition of aqueous urea solution causes corrosion. Crevices may accelerate corrosion due to geometry and high temperatures.	[83]
316SS	500°C under Ar environment	NaCl-KCl-$ZnCl_2$	Oxide layer of Zn, Fe, Cr, Ni formed on surface. Corrosion related to hygroscopicity of $ZnCl_2$, involving Fe, Cr, Ni.	Annual corrosion rate of 316SS alloy: 195 μm/yr after 240 h.	[84]
Ti_2AlNb-based alloy	650 °C for oxidation Room temperature for salt spray testing	High temperature, salt spray, and high temperature-salt spray conditions. Coastal conditions of aerospace hot-end components.	Ti2AlNb alloy forms dense 3 μm oxide layer at 650°C. Cl_2 accelerates chloride volatilization, re-oxidation, and corrosion pit formation.	Unprotected corrosion products were observed to alter oxide layer, causing severe damage.	[85]
Aerospace-grade 80A alloy Filler wires ERNiCrMo-3 and ERNiCr-3	50 cycles of air oxidation and molten salt conditions at 900°C	High-temperature aggressive environment	Protective oxides (Cr_2O_3, NbO, $NiCr_2O_4$) resist hot corrosion. PCGTAW technique suppresses heat-affected zones,	PCGTAW technique shows superior corrosion resistance in hot corrosion environment. Protective oxides like Cr_2O_3, NbO, $NiCr_2O_4$ help resist oxidation.	[24]

			enhancing corrosion resistance.		
FeCrAl, NiCr, NiCrAlY, A625 coatings applied by HVOF Typical base steel alloy T92	Exposure at 600°C for 1000 hours in laboratory scale furnace.	Simulated biomass firing conditions with CO_2, N_2, SO_2, and HCl.	Cr depletion and sulphidation layer formation observed in exposed samples. K_2SO_4 layer formation observed on all coated specimens.	HVOF NiCr coating outperformed T92 alloy in corrosion resistance. No conclusive evidence on the superiority of any coating composition/method.	[86]
IN718 superalloy	600°C, 650°C, and 700°C	Marine-like environment Presence of HCl(g) as catalyst	Two distinct layers: outer layer $NiFe_2O_4$, NiO; inner layer $FeCr_2O_4$, $NiCr_2O_4$.	Corrosion scale on IN718 alloy has two distinct layers.	[87]
Martensitic heat-resistant steel T91	500-700 °C	High-temperature carbon dioxide environment	Outward diffusion of Cr fixed by C, increased diffusion resistance. Reduced Cr content led to increased C diffusion resistance.	Corrosion kinetics of T91 followed a parabolic law. Internal carburization detected underneath corrosion scale in high-temperature CO_2.	[88]
Alumina Hypereutectic metal matrix composite (MMC) Austenitic steel	650 °C	High temperature erosion-corrosion behavior of wear protection materials Investigated at 650°C with high particle velocity in erosion test rig	Alumina: Highest wear loss due to brittle behavior, no oxidation. MMC: Pronounced oxidation intensifies wear loss at high temperatures.	Alumina had highest wear loss due to brittle behavior. Austenitic steel showed most favorable results due to tribo-layer formation.	[89]
T24, T91, Super 304H, Haynes 282 Heat-resistant steels and alloy	Study conducted at 600°C High-temperature environment for corrosion behavior investigation	High-temperature carbon dioxide environment at 600°C	Corrosion kinetics followed parabolic law. Superior corrosion resistance in materials with higher Cr and Ni	Super 304H and Haynes 282 showed superior corrosion resistance.	[88]
Ni− and Fe-based model alloys	Study temperature range: 350 °C–700 °C	Study conducted in molten chloride salts relevant to	Surface diffusion of Ni at solid/electrolyte interface at 350°C.	Dealloying of Fe and Cr in molten chloride salts at 350-700°C. Transition from	[90]

		nuclear reactors.	Grain boundary dealloying prevalent above 500°C.	surface diffusion to grain boundary dealloying with temperature.	
Fe–Cr alloys Alloy $Fe9Cr_3AlSi_3Mo$	500 and 600 °C	Simulated waste incinerator environments N_2-O_2 with HCl, H_2O, SO_2, KCl, $ZnCl_2$ salts introduced	Fe and Cr observed as the most active elements in metal base. Cr presence beneficial, formed protective oxide scales against corrosion.	Alloy $Fe_9Cr_3AlSi_3Mo$ performed best due to protective oxides.	[91]
Anode steel claw materials. Multi-component permeating protective layer.	900°C	Molten cryolite atmosphere at 900°C. Simulated electrolytic aluminium-production environment for anode steel claw.	New technology generated volatile product to prevent corrosion.	Multi-component permeating layer enhanced corrosion resistance in high-temperature environment.	[92]
Alloy C-276 Filler wires ERNiCrMo-3 and E	675°C	Molten state of K_2SO_4-60% NaCl environment at 675°C	ERNiCrMo-3 weldment prone to degradation due to alloy segregation.	PCGTA ERNiCrMo-3 weldment showed higher parabolic constant in corrosion. Major phases identified in the scale: Cr_2O_3, Fe_2O_3, $NiCr_2O_4$.	[93]
Nickel and molybdenum	800°C	High temperature chlorine-containing environments Study of nickel and molybdenum corrosion mechanisms and kinetics	Dissociative adsorption of chlorine molecule impacts corrosion mechanism. Chlorination reactions follow heterogeneous catalysis mechanisms like oxygen reactions.	Molybdenum is more resistant than nickel in high temperature chlorine corrosion. Nickel rapidly consumed above 800°C, molybdenum remains almost inert.	[94]

percolation dealloying are two mechanisms that cause corrosion between metals and molten salts at high temperatures [87]. For example, at high temperatures, salts such as NaCl and Na_2SO_4 actively cause hot corrosion processes in superalloys [101]. According to [24], these interactions result in the production of metallic carbides and oxides, which then react with the molten salts to continue the corrosion process. Furthermore, even at relatively low temperatures, the impact of KCl in O_2/H_2O environments was found to be corrosive to stainless steels, resulting in the production of various oxide morphologies. Elemental segregation to the surface of metal alloys due to high-temperature oxidation might lower stress gradients and impact corrosion rates [23]. Studies conducted on Fe–Cr–B alloys with different Cr contents showed that greater Cr levels improve corrosion resistance by changing borides and preserving periodic layered structures in the corrosion interface; the Cr alloy with a weight percentage of 28.73 wt% showed the best resistance [102]. Additionally, research on unalloyed steel and cast irons in contact with liquid aluminium revealed different behaviours, with the function of graphite lamellas as diffusion barriers and aluminium diffusion leading to the formation of intermetallic compounds [103]. The development of corrosion-resistant alloys can be sped up by using methods such as high-throughput electrochemistry to investigate of materials' deterioration in harsh environments [104]. These understandings are essential for anticipating and preventing corrosion in harsh, extreme conditions.

Empirical evidence suggests that uniform corrosion may result from the breakdown of aqueous urea solution at high temperatures under deposits on stainless steel. Temperature cycling and crevice geometry may further accelerate corrosion [105]. Materials such as alumina, metal matrix composites, and austenitic steel have different wear behaviors when it comes to solid particle erosion at high temperatures. These behaviors are governed by oxidation and erosion, and wear rates are affected by the creation of protective layers [89]. Furthermore, it has been shown that 304 stainless steels that have been exposed to radiation in pressurized water reactor primary water exhibit greater corrosion rates in response to higher radiation doses, which are also associated with changes in oxide microstructures and corrosion kinetics [106].

As reported by Varga et al. [89], metals erode and corrode in severe temperature conditions by a mix of chemical processes and mechanical factors. Increased wear rates are the outcome of mechanical phenomena caused by the relative motion of confined solid particles (third body) and a gas or liquid (second body). By doing so, passivation or protective surface layers may be removed, leaving the bulk surface vulnerable to chemical interactions with ambient oxidizing chemicals. At elevated temperatures, when many regimes may be identified based on oxidation rates, the majority of materials have essential operating temperatures. They include "erosion-dominated" behavior at low temperatures, "erosion-corrosion," and "corrosion-dominated" behavior, depending on temperature and oxidation rates. The formation of persistent oxide scales may significantly increase wear resistance, and high temperatures accelerate the growth of scales in between erosion occurrences. After the oxide scales are thick enough to resist removal by erosive particles, brittle chipping of the oxide scales takes place, which affects the overall erosion-corrosion behavior of metals at extreme temperatures.

The erosion-corrosion behavior of three different wear protection material types—AISI 316, MMC, and alumina ceramic—at 650°C was investigated. Alumina did not oxidize much since it is fragile, but it did exhibit the highest rate of attrition at room temperature and 650°C. MMC demonstrated greater oxidation at high temperatures, which exacerbated erosion rates, in contrast to austenite, which displayed tribo-oxidative behavior but generated a protective tribo-layer, resulting in the most favorable erosion performance. The wear behavior of the materials was shown by comparing the erosion data at two temperatures (45° and 90° impingement angles) and 65 m/s. At both temperatures, alumina showed brittle wear behavior, whereas austenite retained its ductile behavior and MMC changed to a more ductile regime at high temperatures. The findings underscore the disparate erosion-corrosion reactions of distinct materials in high-temperature conditions, underscoring the significance of material selection for maximum efficacy and longevity [89].

The results of Varga et al. [89]'s study on the erosion and corrosion behavior of materials at high temperatures are consistent with the investigations conducted by Derelizade et al. [107] and Singh & Mishra [108]. In their study, Derelizade et al. [107] examined the wear resistance of CrNiAlCY coatings at 900°C and room temperature. They found that the production of protective oxide layers at higher temperatures enhanced the coatings' resistance to wear. In contrast, Singh & Mishra [108] investigated the erosion performance of WC-12Co, Stellite 6, and Stellite 21 coatings at 400°C, highlighting the role that chromium and cobalt's protective oxide layers play in reducing erosion rates. Together, these investigations highlight the vital role protective oxide layers play in improving wear resistance under extreme temperature circumstances, demonstrating the significance of material selection for lifetime and optimal performance [107,108].

3.2 Metal corrosion and high temperature-environment synergy (pressure, chemical species).

By interacting with other environmental factors, extreme temperatures can have a significant impact on corrosion processes. Studies have

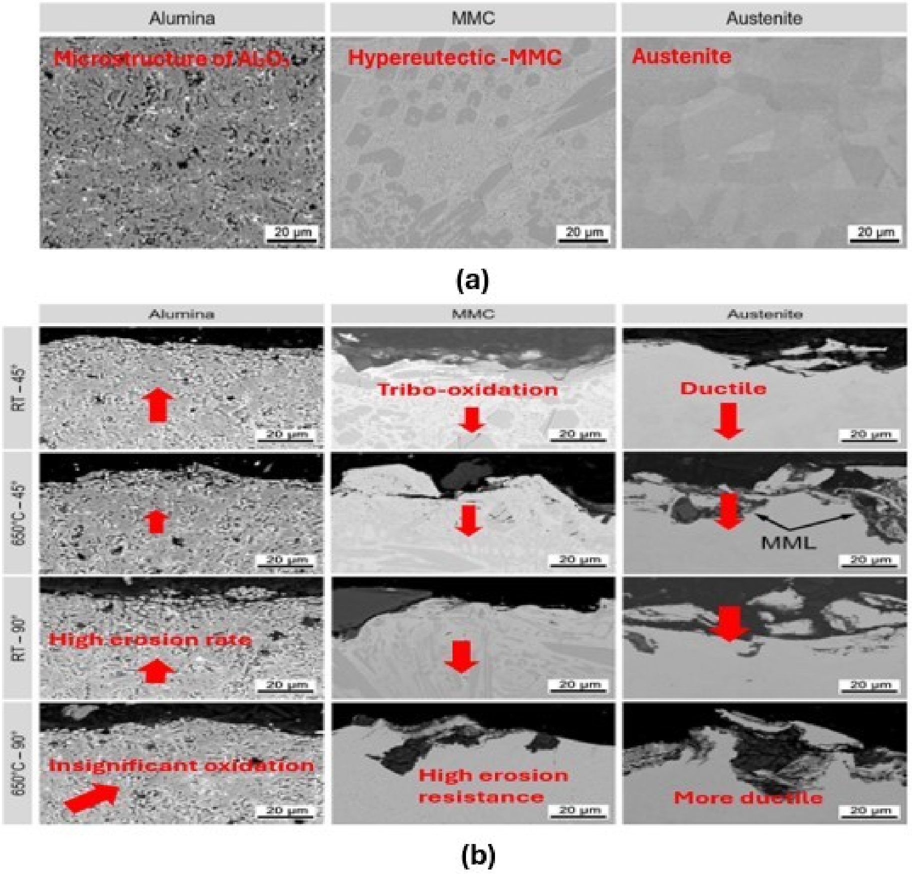

***Figure 1**. (a) Microstructures of the materials examined (b) SEM pictures of the cross-sections under various test circumstances [89]*

indicated that elevated temperatures and oxygen (O_2) can quicken steel's overall corrosion rate [109]. Further evidence of accelerated corrosion owing to variations in surface characteristics and oxygen distribution came from the combined effects of galvanic coupling and crevice corrosion on stainless steel fasteners in chloride environments [110]. Additionally, the research on coastal areas emphasized the significance of comprehending the mutually reinforcing effects of chemical pollution and climate change, underscoring the necessity of comprehensive methodologies to evaluate the cumulative effects on marine environments [111].

Temperatures as high as 1100°C and pressures as high as 300 bars can have a substantial effect on metal corrosion in a variety of industrial environments, including CO_2 pipes, nuclear reactors, and thermal power plants. The significance of pressure in corrosion behavior was demonstrated by studies on materials such as austenitic stainless steel 310 subjected to various pressures at 625°C, which revealed varied oxide structures depending on pressure levels [112,113]. Furthermore, research on pipeline steel in high-pressure CO_2 conditions showed that the cathodic process is aided by hydrogen evolution processes. Corrosion rates rise with temperature first, reaching a peak at 348 K, and then begin to decline [114]. Additionally, different kinds of corrosion on metallic alloys have been observed in pressurized water environments typical of nuclear reactors, highlighting the necessity of considering both general and localized corrosion phenomena in extreme conditions [115]. To meet these challenges, high-temperature and high-pressure electrochemical corrosion testing methods have been essential in comprehending and preventing deterioration in aqueous processing at increased pressures and temperatures [116].

At high temperatures, chemical species are essential in speeding up metal corrosion. The chemical reactivity of solid materials is determined by their crystal and defect structures, which impact corrosion processes in high-temperature conditions [117]. Acid gas species such as CO_2, H_2O, SO_2, and H_2S, for example, greatly accelerate the high-temperature corrosion of heat exchanger materials in boilers under oxy-combustion conditions [118]. CO_2 also accelerates the corrosion rate of water wall materials. According to molecular dynamics simulations, stress gradients are lessened when components like Al and Cr separate to the surface during oxidation. This changes the adsorption and diffusivity of oxygen and hydrogen, which in turn affects the pace of corrosion [119]. High-temperature water corrosion is further influenced by the solubility and dissociation of attacking species and corrosion products in aqueous systems up to supercritical temperatures [120]. Oxygen, air, water vapor, sulphur dioxide, nitrogen, and other gaseous components can also have an impact on high-temperature corrosion in atmospheres containing Cl_2 and/or HCl [121].

3.2.1 Control of corrosion of metal at elevated temperatures following variation in pressure and chemical species

Based on the research findings, several solutions may be used to avoid the corrosion of metals at extreme temperatures under variable pressure environments. For example, cathodically polarizing the metal components with an electro-active molten salt flux can be used to shield titanium and its alloys against air attack at high temperatures [122]. The creation of a protective oxide scale rich in chromium and aluminum is necessary to improve the high-temperature corrosion resistance of stainless steels. This can be done by surface treating the steel or alloying it with elements such as Mn, Al, Si, or rare earth metals [123]. Furthermore, high-chromium coatings can effectively protect the substrate from corrosion in aggressive environments, such as low oxygen partial pressure combustion atmospheres, as seen in diffusion chromized steel and high-velocity oxy-fuel coatings [124].

The formation of new compounds under pressure, the oxidation behavior of metal matrix composite hard facings, the corrosion resistance of welds, and studies have demonstrated that the welding seam of coiled tubing is more prone to corrosion than the base material under service conditions [125], that high-pressure environments can result in the creation of new compounds with unconventional stoichiometries, offering exotic properties like high-temperature superconductivity [126], and that the interface between materials, as in Mg-Ti composites, is a crucial factor in determining corrosion resistance of materials. Furthermore, different corrosive environments are resistant to cermet particle-reinforced hard facings in different ways. Cr_3C_2-Ni hard facings perform better in oxidative and sulphate/phosphate conditions, while TiC-NiMo hard facings exhibit superior resistance against carbonate ions and chlorine up to 700°C [127]. Materials may be carefully selected to prevent corrosion in high-pressure and high-temperature environments by taking these considerations into account.

Different chemical species and circumstances can regulate the rate of metal corrosion at high temperatures. Studies have indicated that the dissolution of molybdenum (Mo) in alloys leads to an increase in chromium (Cr) assimilation, as exemplified by the wall-jet ring-disc (WJRD) arrangement [128]. Furthermore, the potential of environmentally benign corrosion inhibitors to stop metal from corroding at high temperatures has been investigated [129], with an emphasis on inhibitors that work between 323 and 373 K. Controlling corrosion in combustion or fuel cell conditions requires an understanding of the thermodynamic characteristics of volatile hydroxides and oxyhydroxides generated at high temperatures [130]. The durability of oxide layers, solubility of gases, and dissociation of acids are some of the factors that affect corrosion in high-temperature aqueous solutions and influence the choice of materials that work well in these environments [131].

3.3 Novel materials and coatings that withstand metal corrosion at high temperatures

Elevated temperatures exert a notable influence on the creep, deformation behaviors, and structural reactions of metals and alloys [132,133]. When exposed to different temperatures and water content atmospheres, high temperature alloys used in solid oxide fuel cell systems, such as alloy 625, SS309, and alloy 318, undergo oxidation and Cr_2O_3 evaporation mechanisms; lower temperatures reduce oxidation rates for certain alloys [18]. High temperatures can cause high-temperature corrosion in hostile situations like the power generating sector. This can seriously impair the performance of nickel-based superalloys used in gas turbine engine applications. The integrity and service life of the alloy may ultimately be impacted by this corrosion, which can cause a number of deterioration processes, including fluxing, hot corrosion, Sulphidation, and corrosion fatigue [134–137]. In order to improve their resistance to corrosion and the production of oxides, nickel-based superalloys are meticulously crafted with metals such as copper, molybdenum, and chromium. These components are essential for withstanding harsh circumstances in conditions with high temperatures [135]. Furthermore, it has been shown that single-crystal castings have better creep strength and thermal fatigue resistance than polycrystalline castings, which makes them perfect for enduring the harsh operating conditions of gas turbine engines [138]. Moreover, it presents considerable technical problems to sustain components at high temperatures under cyclic thermal and mechanical loadings, necessitating careful study of material reactions and behaviors [139]. Conventional corrosion inhibitors may desorb from metal surfaces at high temperatures, which would decrease their efficacy and speed up corrosion, particularly at 323 K [129]. Metal oxide-based scales may be formed by hot corrosion, which usually occurs between 250 and 450°C. These scales can provide some protection; however the Pilling-Bedworth ratio indicates that the porosity of the scale affects how effective the scale is [140]. High-temperature resistant alloys, which incorporate elements like Y and Re to improve corrosion resistance and prevent the separation of protective layers, have been developed as novel materials to combat high-temperature corrosion. These materials exhibit improved resistance to extreme temperature environments [141]. These cutting-edge compounds are designed to give metals working in harsh, high-temperature environments more protection and endurance.

High entropy alloys (HEAs) made by laser-based additive manufacturing, high temperature metallic glasses with crystallization temperatures above 700°C, and nanocarbon materials like carbon nanotubes (CNTs) and graphene are examples of novel materials intended for extreme temperature environments to prevent metal corrosion. Because of their enhanced mechanical strength, electrical conductivity, and thermal stability, carbon nanotubes (CNTs) and graphene are the perfect materials for high-temperature electronics and wide-temperature structural building [142]. HEAs made by laser-based additive manufacturing, notably AlCoFeNiTiV0.9Sm0.1 and AlCoFeNiV0.9Sm0.1, show high corrosion resistance in challenging conditions, such as corrosive syngas atmospheres at extreme temperatures [143]. Furthermore, a promising new class of materials for harsh environments such as those found in the nuclear and aerospace industries is presented by high temperature metallic glasses, which combine the mechanical properties of metals with the chemical durability of glasses, with crystallization temperatures above 700°C [144].

Oxide-dispersion-strengthened NiCoCr-based alloys, such as GRX-810, are novel materials that are specifically designed for extreme temperature environments. They are made using laser-based additive manufacturing, and they offer superior strength, creep performance, and oxidation resistance [145]. These materials have superior mechanical properties, such as enhanced strength, improved oxidation resistance, and over 1,000 times better creep performance [145,146]. The alloys' microstructure is improved by the addition of nanoscale oxides, which improves creep resistance under a variety of stresses and directions [147]. Moreover, SiC opacifier-containing fibre aerogels, like directional ZrO_2 fibre aerogels (SZFAs), exhibit notably lower high-temperature thermal conductivity, improving their insulating capabilities in harsh conditions [148]. High-entropy carbides and borides show promise for harsh circumstances in nuclear reactors and advanced turbine engines because of their unique features such as enhanced irradiation resistance, high hardness, and strength [149].

Several materials and techniques have been investigated in the development of materials to avoid corrosion in high temperature environments. Materials resistant to corrosion have been produced using self-propagating high-temperature synthesis (SHS), which has shown promising results for use in harsh locations such as the Arctic [150]. Furthermore, components in energy systems, especially those involving the disposal of waste and the burning of biomass, may benefit from the use of thermally sprayed coatings, such as Ni-Cr-B-Si and Ni-B-Si alloys [151]. The significance of wear-resistant materials like alumina, metal matrix composites, and oxidation-resistant steels has also been brought to light by research on solid particle erosion at high temperatures, which illustrates how these materials behave under erosive-corrosive conditions at extreme temperatures [89]. Additionally, research has been done on the development of coatings from post-processing chips of Ni-based alloys and austenitic steels using High-Velocity Oxy Fuel (HVOF) technology to evaluate their corrosion behaviour at high temperatures, advancing the field of materials engineering for harsh environments [152]. Finally, novel techniques such as spray graphitization have been suggested to shield carbon steel from high-temperature corrosion from molten salt, providing an affordable remedy for uses such as Concentrated Solar Power (CSP) technology [153].

According to CzupryŴnski et al. [151] and illustrated in Figure 3, the process of flame powder spraying entailed employing a contemporary and accurate oxy-acetylene system for manual flame powder spraying CastoDyn DS 8000 to apply thermally sprayed coatings on a gas-tight pipe wall of a powder boiler. Before being sprayed, the samples' surface was cleaned using a cabin sandblaster to remove rust, scale, and grease. This was followed by brushing and chemical cleaning with tetrachloroethylene [151]. Abrasive blasting was used in the surface preparation to get a final surface roughness of Ra = 12 μm and Rz = 85 μm

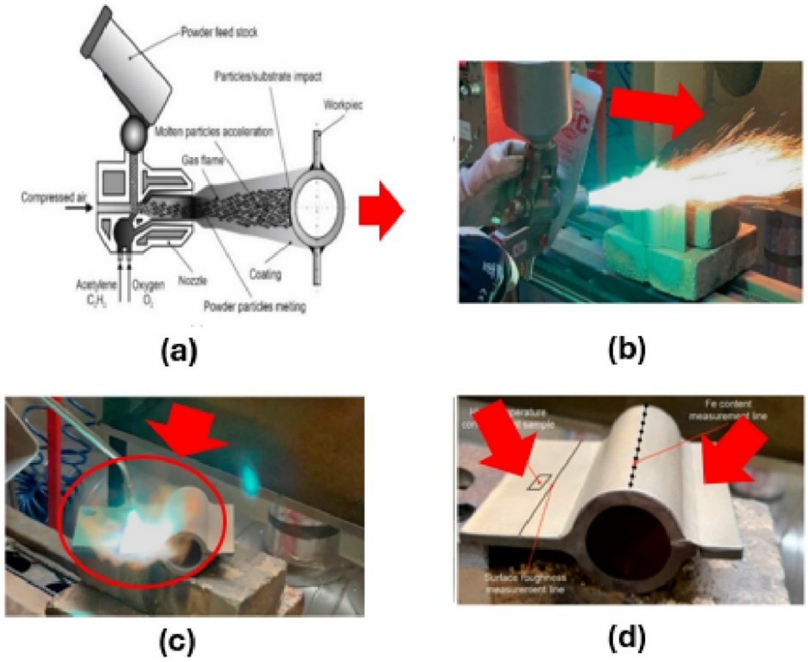

Figure 3*.The steps involved in flame powder spraying: (a) a manual flame powder spray burner diagram; (b) a view of a flame powder spray test using a CastoDyn DS 8000 burner for a remeltable Ni-Cr-B-Si alloy coating; (c) a view of the remelting test of the coating sprayed with a self-fluxing powder made of the remeltable Ni-Cr-B-Si alloy; and (d) a view of the sample covered by the coating that prevents corrosion at high temperatures [151].*

[151]. According to ISO 2063-1 standards, adequate substrate surface cleaning and preparation prior to spraying was essential for achieving satisfactory coating adherence.

A smooth coating surface was ensured by reducing interior porosity by remelting the sprayed coating over an oxy-acetylene flame. Furthermore, to achieve high-quality coatings resistant to corrosion and erosion, appropriate surface preparation, restricting the amount of heat applied to the base material, and managing the quantity of Fe and NiO oxides were crucial [151]. To successfully producing and applying thermally sprayed coatings to protect boiler components against high-temperature corrosion in extreme situations, the flame powder spraying technique shown in the figure 3 provided a complete solution.

3.4 Coatings that are designed for extreme temperature environments to avert metal corrosion

Different kinds of coatings have been produced to prevent corrosion and safeguard metals in high-temperature situations. For example, vitreous ceramic-like enamel coatings have demonstrated a high degree of corrosion resistance in boiling brines, high temperature/high pressure steam, and acidic conditions with CO_2-H_2S gases, which qualifies them for use in industrial operations [154]. Phase composite ceramic thermal barrier coatings, which provide advantages including thermal stability, low thermal conductivity, and erosion resistance, have also shown higher performance in gas turbine engines [31]. NiCoCrAlYHfSi and CoCrAlYTaCSi, two thermally sprayed coatings, have demonstrated encouraging results in high-temperature corrosion assessment in molten salt conditions, surpassing conventional steels like P91 and H800 [82]. Moreover, self-healing anti-icing coatings, such as the fluorinated graphene-based coating, have been developed to endure difficult circumstances such low temperatures, strong acids, and alkalis, guaranteeing long-lasting anti-icing efficacy in harsh conditions [155]. Ni-Cr-based coatings applied by thermal spray techniques have also shown promise in preventing hot corrosion and oxidation of components, especially in boiler environments with high temperatures [156]. Further information on the results of different studies on the coatings for high temperature corrosion protection is presented in Table 2.

Table 2. *Overview of previous studies on coatings that are designed for extreme temperature environments to avert metal corrosion*

Metal/Material coated	**Coating material**	**Study temperature**	**Effect of coating on coated metal/material**	**REF**
Low-alloy and carbon steel components. Tubulars.	Vitreous ceramic-like enamel coatings Thickness up to 300 µm	High temperature corrosion resistance testing conducted	Enamel coatings offered high corrosion resistance. insignificant compositional and structural degradation observed.	[154]
Phase composite ceramic TBCs Dual-phase and tri-phase structures	Two-phase zirconia-based TBCs Triple-phase TBC with CMAS resistance.	Isothermal heating at 1300°C for 50 or 100 hours.	Phase composite TBCs showed lower solid particle erosion rates unlike thermal aging.	[31]
Base material 1.4923 Used as cost-efficient construction material for power equipment components	CoCrAlYTaCSi, NiCoCrAlTaReY, NiCoCrAlY, NiCoCrAlYHfSi coatings	800 °C (Cyclic conditions: 1 h heating, 20 min cooling)	CoCrAlYTaCSi coating showed best corrosion resistance. NiCoCrAlY-coated specimen showed severe corrosion attack.	[82]
FeCrAl, NiCr, NiCrAlY, A625 coatings applied by HVOF T92 base steel alloy	FeCrAl, NiCr, NiCrAlY, A625 coatings applied by HVOF HVOF NiCr coating outperformed T92 alloy.	600 °C for 1000 hours in furnace.	NiCr coatings showed greatest metal losses. FeCrAl coating exhibited significant improvements over substrate alloy with minimal damage.	[86]
Ni–Cr-based coatings Ni- and Fe-based alloys	Ni–Cr-based coatings effective in high-temperature oxidation and corrosion. Coatings include chromia and Ni–Cr-Co-based spinels for protection.	900 ℃	Ni–Cr-based coatings provide protection against oxidation and hot corrosion. Coating composition and microstructure influence oxidation and hot corrosion properties	[156]
Zircaloy-4 substrate Cr_2AlC-based coatings	Cr_2AlC MAX phase Alumina-forming textured coatings on Zircaloy-4 fuel claddings	550°C	Growth of α-Al_2O_3 scale during high-temperature oxidation in steam. Thin passivating Cr_2O_3 layer during hydrothermal corrosion in autoclave.	[157]
Cu	Magnesium and aluminum coatings applied on copper for protection.	Mg coatings: up to 450-500°C Al coatings: up to 800-850°C	Mg and Al coatings improved the protection performance of copper. Al coatings showed best performance in high temperature environments.	[158]
Metal products protected from corrosion in liquid metal environments	Multilayer ceramic coatings Developed using low temperature heterophase transfer and microarc oxidation methods	400-600°C	The applied coating protected the metal from corrosion in aggressive liquid metal environments.	[159]

Aircraft components Various types of high-temperature coatings	Simple and multi-component protective coatings Used at temperatures up to 1200 – 3000	1200 – 3000°C.	Enhances durability and resistance to high temperatures. Protects metal/material in aggressive environmental conditions up to 3000°C.	[160]
Molten or partially molten material projected to form coating overlay. Any material not degrading upon heating can be applied.		700–900 °C	The applied coatings developed shielding oxide film to limit metal loss by oxidation.	[161]
316 L steel	thin-film Aluminum-oxygen-nitrogen (Al - O – N) and aluminium nitride (AlN) coatings	700 °C for 500 hours	Increased resistance to high-temperature gas corrosion due to the effect of filling the interstitial space with oxygen, increase in the number of structural distortions of the crystal lattice, thereby preventing oxidation and hydrogenation with the subsequent formation of gas-filled bubbles.	[162]
nickel-based superalloy K444	yttrium-modified aluminide coating	950^{O}C, 1000^{O}C, and 1050^{O}C	The higher the deposition temperature, the higher the yttrium content of the coating, the faster the film-forming speed of α-Al_2O_3, and the better the high temperature oxidation resistance and thermal corrosion resistance of the coating.	[163]
Inconel 738LC	nano Yttria Stabilized Zirconia (YSZ) with different percentages of Carbon Nano Tubes (CNTs)	650^{o}C, 750^{o}C, 850 ^{o}C, and 950^{o}C	All layers of coatings exhibit good hot corrosion resistance compared with uncoated specimen and less change in weight than that of the corresponding bare specimen. The addition of CNTs enhances the properties of the coating layer, such as porosity and voids are decreased.	[164]

4 CONCLUSION

The following conclusions can be drawn from the review of relevant studies on the corrosion of metals at elevated temperatures:

i. Sulfidation, fluxing, hot corrosion (types I and II), and corrosion fatigue are some of the intricate mechanisms involved in the high temperature corrosion of metals. Materials must be shielded from corrosive environments by protective oxide scales like Cr_2O_3 and $MnCr_2O_4$.

ii. Metal corrosion is exacerbated by a combination of environmental conditions, including temperature, chemical species, and pressure. For instance, high temperatures and oxygen can speed up the overall rate of corrosion in steel, but under oxy-combustion circumstances, acid gas species like CO_2, H_2O, SO_2, and H_2S greatly exacerbate the corrosion of heat exchanger materials in boilers.

iii. High entropy alloys (HEAs), high-temperature metallic glasses, nanocarbon materials like graphene and carbon nanotubes, and oxide-dispersion-strengthened alloys like GRX-810 are examples of novel materials made to resist metal corrosion at high temperatures. In harsh conditions, these materials provide enhanced strength, oxidation resistance, and creep performance.

iv. A variety of coatings, such as phase composite ceramic thermal barrier coatings, vitreous ceramic-like enamel coatings, and Ni-Cr-based coatings applied by thermal spray processes, have been developed to safeguard metals in high-temperature situations. The ability of these coatings to withstand corrosion in harsh environments has demonstrated encouraging results.

v. Surface preparation, coating microstructure, material composition, and application techniques are some of the factors that affect how effective corrosion protection methods are. For example, the flame powder spraying technique, which applies thermally sprayed coatings, requires adequate surface cleaning and preparation to achieve satisfactory coating adherence and corrosion resistance.

5. IDENTIFIED GAPS IN LITERATURE

The review of previous studies that are relevant to the corrosion of metals at elevated temperatures has revealed the following gaps in knowledge which border on the combined influence of several environmental elements and corrosion behaviour at the micro and nano scales:

i. Although certain synergistic impacts were highlighted by the study, a thorough knowledge of the simultaneous interactions between several environmental elements is still lacking. Further study is needed to develop prediction models that can effectively take into consideration the intricate interactions between different environmental factors and corrosion behaviour.

ii. The macro-scale corrosion processes are the focus of this work. Further investigation into corrosion processes at the micro and nanoscales is necessary, especially for sophisticated materials with intricate microstructures.

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IZVOD

KOROZIJA METALA U USLOVIMA VISOKE TEMPERATURE: PREGLED

Ovaj rad je pregledao prethodne studije relevantne za mehanizme korozije metala na ekstremno visokim temperaturama, kombinovane efekte pritiska i hemijskih vrsta na procese korozije i razvoj inovativnih materijala i premaza napravljenih da izdrže ove izazovne uslove. Složene interakcije između temperature, pritiska i hemijskih vrsta su istaknute u istraživanju kao faktori koji ubrzavaju stope korozije metala u različitim industrijskim okruženjima. Podaci iz brojnih eksperimentalnih studija i industrijskih primena analizirani su kao deo detaljnog pregleda literature sprovedenog za ovo istraživanje . Prethodne studije su objavile da su mehanizmi korozije, uključujući fluksiranje, vruću koroziju, sulfidaciju i zamor od korozije, uključujući zaštitne oksidne skale, presudni za održavanje integriteta materijala. Novi materijali dizajnirani za ekstremnu temperaturnu otpornost, kao što su legure visoke entropije, metalna stakla na visokim temperaturama i legure ojačane oksidnom disperzijom, pokazuju superiornu snagu, otpornost na oksidaciju i performanse puzanja, uključujući zaštitne premaze, poput staklastog tela nalik na keramiku emajli i fazne kompozitne keramičke termičke barijere. Da bi se poboljšala izdržljivost i performanse metala u ekstremnim okruženjima, istraživanje je istaklo značaj sastava materijala, mikrostrukture premaza i tehnika primene u određivanju efikasnosti metoda zaštite od korozije. Na osnovu ovih nalaza, studija je preporučila dodatna istraživanja razvoja i optimizacije naprednih materijala i premaza za posebne primene na visokim temperaturama, kao i integraciju ovih rešenja u industrijske procese.

***Ključne reči**: visokotemperaturna korozija, oksidacija, zaštitni premaz, nezaštitni premaz, novi materijali za ekstremna okruženja*

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