ISSN: 0973-3469, Vol.20, (Special Issue) 2023, Pg. 01-12

Material Science Research India

www.materialsciencejournal.org

Review of Thermal Spray Coatings Perform in Protecting Boiler Steels against Corrosion at High Temperatures

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Abstract

Failure of boilers can cause huge economic loss to the power plants. In high temperature and aggressive working conditions erosion, hot corrosion and abrasions are most responsible factors for failure of boiler steels. Thermal spray coatings are the preferable method to minimize the cause of failures of the boiler steels due to these problems. Among different thermal spray techniques. By utilizing the HVOF process, it is possible to produce coatings with high micro-hardness and low porosity, making it an advanced and effective method that is currently undergoing rapid development. In this paper a review study regarding the performance of thermal spray coatings deposited on boiler steels against the hot corrosion has been presented. The outcomes of this research have the potential to assist in identifying the optimal coating combination and application technique to prevent the deterioration of boiler steels.

Article History

Received: 23 April 2023

Accepted: 04 August 2023

Keywords

Boiler Steels;
Coatings;
Hot Corrosion.

Introduction

Corrosion losses in India are estimated at about 6500 US dollars per year.[1] At high temperatures, corrosion can lead to hot corrosion, a process that accelerates oxidation.[2] This occurs when the metal surface is covered with a salt layer. Numerous reactive species, such as ash content, moisture content, and alkali earth metal content, are produced as a result of fuel combustion, and these substances are highly corrosive in nature. Potassium, chlorine, sulfur, calcium, and silicon salts are formed as a result of rice husk combustion.[3] Deposits of these salt species can accumulate on the surfaces of fireside components. The working temperature in boiler environments ranges from 500°C to 900°C.[4,5] When boiler components are subjected to high temperatures, a layer of oxide scale develops on their surfaces as a protective measure. The combination of salt species with the protective oxide layer leads to the dissolution of the oxide, leaving the component vulnerable to corrosion. The chlorine present in the environment influences the protective oxides by forming the gas phases of Cl2, HCl, NaCl, and KCl. When the salt species dissolve the protective oxide layer, the surface becomes vulnerable to active oxidation, which can increase the rate of oxidation

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Doi: http://dx.doi.org/10.13005/msri.20.special-issue1.01

and lead to direct corrosion.[6-7] Corrosion in boilers under a high-temperature environment is known as hot corrosion. This is induced by a thin film of fused salt deposits present in the environment. The two main types of hot corrosion are Type 1, also known as high-temperature hot corrosion, and Type 2, also known as low-temperature hot corrosion. Significant economic losses can be incurred as a result of hot corrosion, which may necessitate extra maintenance or forced outages of boiler materials.[8]

The considerable efforts have been done to reduce the economic losses caused due to corrosion attack. To mitigate the effects of hot corrosion, different strategies have been implemented, including incorporating corrosion inhibitors, using high-chromium materials, and applying anti-corrosion coatings. Out of all the available methods, the application of coatings is considered to be the most efficient and effective approach as the use of inhibitors has proven to be inadequately successful, and incorporating materials with high chromium content would significantly escalate the expenses.[9] The coating materials used in high temperature applications must have the characteristics to form a stable and the slow-growing surface oxide in order to provide good service behaviour.[10] Various coating processes are used to improve the surface properties of various metals for different applications. The thermal spray coating process is a widely recognized method for enhancing surface wear resistance, with variations such as plasma spray, arc spray, detonation gun spray, and flame spray.[11]

This paper aimed to present the different coating deposition techniques, coatings, and their behaviour in high temperature conditions of boiler environments.

Types of Hot Corrosion

There are two types of hot corrosion that can occur at different temperature ranges. Low temperature hot corrosion, also known as Type II, happens at temperatures between 600-750°C, while high temperature hot corrosion, also known as Type I, occurs at temperatures between 800-950°C.[8] Various factors, such as velocity, alloy composition, temperature cycles, and erosion process can impact both types of hot corrosion. Type I hot corrosion is caused by a fluxing process where the chemistry of sodium sulfate deposit is altered, allowing sulfur to penetrate the metal underneath. This penetration causes a reduction in the chromium content of the substrate metal, leading to oxidation and the formation of a porous oxide scale. In Type-II hot corrosion, sulfates of the base metal react with alkali metal, resulting in the creation of a eutectic with a low melting point that inhibits the development of protective oxides.[12] Due to their lower melting point, Ni-based coatings are more prone to degradation in environments containing sulfur under Type-II hot corrosion. Type-II corrosion is characterized by pitting attacks and, under microscopic observation, shows minimal sulfide formation with no indications of chromium depletion.[13]

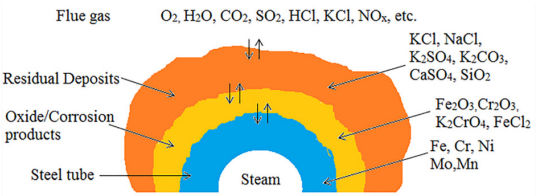

Fig. 1: Schematic illustration of reactive/ corrosive environment surrounds the biomass fired boiler[16]

Mechanism of Hot corrosion

High-temperature hot corrosion starts with the breakdown of the protective oxide layer, which then allows the molten salt to directly attack the underlying substrate material. This breakdown can result from erosion, erosion-corrosion, thermal stresses, and chemical reactions. Two mechanisms have been proposed for the propagation stages of Type-I hot corrosion, namely sulphidation-oxidation and salt fluxing.[14] Figure 1 shows the schematic illustration of reactive/corrosive environment surrounds the biomass fired boiler. At first, the salt fluxing mechanism was suggested by Goebel and Pettit *et al*., which implies that the molten salt may cause the surface oxide layer to lose its protective efficiency due to fluxing of this layer. This can be either basic type or acidic type of fluxing. Basic fluxing occurs when oxides combine with oxygen to form anions, whereas acidic fluxing occurs when oxides decompose into cations and oxygen. Acidic fluxing is more severe than basic fluxing because it leads to a more intense oxidation reaction, especially when the oxidation activity in the molten salt is significantly reduced. On the contrary to basic fluxing, acidic fluxing has the ability to sustain itself, as the degree of salt displacement from stoichiometry does not intensify with the advancement of the reaction.[15]

Various Stages in Hot Corrosion

The hot corrosion mechanism of boiler steels typically involves several stages leading up to component failure:

Stage I

(Incubation Period) In the beginning phase, the reaction follows a pattern comparable to typical oxidation reactions.

Stage II

(Initiation Stage) At this point, corrosion is accelerated compared to the incubation stage.

Stage III

(Propagation Stage) During this stage, corrosion occurs at a very rapid rate.

After Stage III, the components ultimately fail.[16]

Thermal Spray Coatings

Thermal spray coatings encompass various techniques aimed at managing the detrimental effects of high temperatures. This approach involves applying an additional layer of materials that are resistant to degradation onto the surface of steel. This layer serves to impede the rate of corrosion-oxidation, thereby slowing down or preventing material degradation, which can result in a prolonged operational lifespan for the component. The process of thermal spray coating entails the application of safeguarding substances, like ceramics, metals, or specific polymeric materials, onto the surface of the underlying substrate that necessitates protection..[17-18] The spray gun receives the coating material and expels it onto the substrate surface at a high velocity after heating it. The material adheres to the substrate surface through a combination of adhesion and diffusion upon solidification. Flame spray, electric arc deposition, plasma spray coating, high velocity oxy-fuel coating, detonation gun deposition, and cold spray coating are among the thermal spray processes that exist. Each of these methods has its advantages and disadvantages. To select the appropriate thermal spray process, the bond strength, spray velocity, oxide formation, etc. factors among others are taken into consideration. The suitability of each available technique is determined by these factors.[19]

Coatings Tested under Aggressive Environments by Various Researchers

The comprehensive review of recent research papers focussing on the studies about the high temperature corrosion behaviour of different coatings in the reactive environments is presented in Table 1 as follows:

Table 1: Tabular representation of various behavioural studies of coatings under aggressive environments

S. No.	Author	Substrate	Coating	Coating Method	Environment
1	Reddy *et al.*,[20]	MDN 420 alloy	70% NiCrAlY+ 25% Cr_2O_3+5% YSZ and 70% NiCrAlY+ 30% TiO_2	Plasma spray method	Mixture salt of Na_2SO_4 +60 % V_2O_5 at 700°C
2	Dolekar *et al.*,[21]	Inconel 718	CoNiCrAlY + YSZ and YSZ/$Gd_2Zr_2O_7$	EB-PVD	Mixture of salts of NaCl, Na_2SO_4, and V_2O_5 at 1000 °C
3	Singh *et al.*,[22]	T22	Ni-22Cr-10Al-1Y- SiC (N) and Ni22Cr-10Al-1Y	HVOF	At 900°C in Na_2SO_4-60wt%V_2O_5 molten-salt environment.
4	Singh *et al.*,[23]	T22	NiCrAlY-SiC and NiCrAlY-B4C	HVOF	Na_2SO_4+60% V_2O_5 environment at high temperature of 900° C
5	Singh *et al.*,[24]	T22	Ni-22Cr-10Al-1Y-B4C (nano sized) and Ni-	HVOF	In SiC tube furnace at temperature of 900°C

			22Cr-10Al-1Y-B4C (micro sized)		
6	Singh *et al*.,[25]	T91	NiCrAlY	HVOF	At a temperature of 900°C in normal air SiC tube furnace
7	Lone *et al*.,[26]	Superni-75	Cerium oxide	Electroless process	In molten salt environ -ment of Na_2SO_4–60%V_2O_5 at 900 °C
8	Bala *et al*.,[27]	SA 516 alloys and SA-213 -T22	Ni-50Cr	Cold spray process	Na_2SO_4–60% V_2O_5 under cyclic conditions and at high temperature of 900 °C.
9	Mittal *et al*.,[28]	T91	Ni-Cr and Stellite-21	D-Gun spray process	In the presence of air and Na_2SO_4-60% V_2O_5 salt mixture at 900˚C
10	Nithin *et al*.,[29]	MDN 321 and Superni 76	CoCrAlY + Al_2O_3 + YSZ and CoCrAlY + CeO_2 and NiCrAlY as a bond coat	Plasma sprayed	In Na_2SO_4-60%V_2O_5 enviroment exposed to 700 °C
11	Dolekar *et al*.,[30]	Inconel 718	CoNiCrAlYas bond and yttria-stabilized zirconia (YSZ) and YSZ/$Gd_2Zr_2O_7$	HVOF and Electron beam physical vapor deposition (EB-PVD)	30% NaCl, 35% V_2O_5, and 35% Na_2SO_4 at 1000 °C
12	Singh *et al*.,[31]	T-91	Ni_3Al and TiO_2	HVOF	Na_2SO_4-60% V_2O_5 environment at 900ºC
13	Singh *et al*.,[32]	T22	Ni–20Cr, Ni–20Cr–TiC and Ni– 20Cr–TiC–Re	Cold spray process	Na_2SO_4-60%V_2O_5 at 900ºC
14	Jafari and Sadeghi[33]	16Mo3 and Sanicro-25 steels	Ni21Cr, Ni5Al, and Ni21Cr7AlY	HVAF	At 600 °C for 168 h in ambient air under KCl and 50-50 mol% KCl–K_2SO_4 salts
15	Sadeghi meresht *et al*.,[34]	16Mo3	NiCrAlY and NiCrMo coatings	HVAF	Chloridizing-oxidizing environment with and without a KCl deposit, at 600 °C
16	Eklund *et al*.,[35]	16Mo3	NiCr, NiAl and NiCrAlY	HVAF	O_2 + H_2O and O_2 + H_2O + KCl at 600°C
17	Sundare-san *et al*.,[36]	T91	CoCrAlY, NiCoCrAlY, and NiCr	Atmospheric Plasma Spray (APS) and Detona-tion spray (DSC)	Na_2SO_4-K_2SO_4-Fe_2O at 650°C
18	Singh *et al*.,[37]	T22	65NiCr–Cr_3C_2, 80NiCr –Cr_3C_2, 90NiCr–Cr_2C3 and NiCr	HVOF	Na_2SO_4-60 wt% V_2O_5 salts at 800°C
19	Singh *et al*.,[38]	T22	100wt%Cr_2O_3, 90wt% Cr_2O_3–10wt%TiO_2, and 80wt%Cr_2O_3–20wt%TiO_2	HVOF	Na_2SO_4–60wt%V_2O_5
20	Wang *et al*.,[39]	T22	NiCrB and NiCrTi	Arc sprayed	Na_2SO_4-10 wt.% NaCl salt at temperature of

					800 °C
21	Abu-warada *et al*.,[40]	T24 and T92 steels	NiMoCrW and CoNiCrAlY	HVOF	NaberthermLT5/12/P330 furnace by following the standard ISO/FDIS 17224:2014 at 650 ◦C
22	Bhatia *et al*.,[41]	T91	75% Cr_3C_2- 25% (Ni-20Cr)	HVOF	Na_2SO_4-60 wt.% V2O5 at 550,700 and 850°C.
23	Singh *et al*.,[42]	T22	Cr_2O_3	Plasma sprayed	60% Na_SO_4–40% V_2O_5 at 850°C
24	Zhou *et al*.,[43]	P91	Cr_3C_2-NiCrMoNbAl and Cr_3C_2-NiCr	HVOF	6.5% NaCl+34.5% KCl +5 % Na_2SO_4 at temperature of 650°C
25	Bala *et al*.,[44]	SA516	Ni-50Cr and Ni-20Cr	HVOF	At 700 ± 10 °C and volumetric flow of flue gases 16% CO_2 and 3% O_2
26	Sadeghi and Joshi[45]	EN 16Mo3	FeCrNiMoBSiC coatings	HVOF and HVAF	At temperature of 600 ± 3 °C with and without KCl salt
27	Jafari *et al*.,[46]	16Mo3	Ni21Cr, Ni5Al, Ni21 Cr7Al1Y and Ni21 Cr9Mo coatings	HVAF	at temperature 600°C in an air furnace up to 168 h in presence of KCl
28	Fantozzi *et al*.,[47]	P92	Cr_3C_2-25NiCr, Cr_3C_2 -50NiCrMoNb and Cr_3C_2-37WC18NiCoCr coatings	HVOF and HVAF	At temperature of 400, 450, 500 and 550 °C under KCl deposits
29	Kaushal *et al*.,[48]	T22	Ni20Cr	HVOF , D-Gun, and cold sprayed	Na_2SO_4-60% V_2O5 at 1173 K (900 °C)
30	Kai *et al*.,[49]	ASTM1020 steel	NiCrC conventional and nano coating	HVOF	At temperature of 500 -750°C under Na_2SO_4 –30% K^2SO_4
31	Liu *et al*.,[50]	TP347H stain less steel, laser-cladded C22 and C22 alloy	-	-	In molten alkali chloride salts at temperature of 450–750°C
32	Zhen *et al*.,[51]	Inconel-740	-	-	In simulated conditions at temperature of 750℃
33	Awadi *et al*.,[52]	Inconel 738 and 617	-	-	At temperature ranges of 700, 800 and 900°C in aggressive environment of NaCl and Na_2SO_4
34	Rani *et al*.,[53]	ASTM-SA 210-A1	Cr_2O_3-75%Al_2O_3	Detonation gun spray technique	Na_2SO_4-60%V_2O_5 at 900°C
35	Thakare *et al*.,[54]	P91	75Cr_3C_2-25NiCr	Detonation gun	boiler environment at 650°C
36	Somervuori *et al*.,[55]	AISI 316 steel plates	NiCr and NiCrBSi	APS, HVOF, and HVAF.	0.5% and 3.5% NaCl solutions
37	Abu-warda *et al*.,[56]	T24	NiCr	HVOF	KCl, NaCl, Na_2SO_4 and K_2SO_4 at 650 ºC

38	Matikainen *et al.*,[57]	Metal substrates	Cr_3C_2-50NiCrMoNb and Cr_3C_2- 37WC-18NiCoCrFe	HVAF and HVOF	-
39	Chatha *et al.*,[58]	T91	Cr_3C_2-NiCr	HVOF	Na_2SO_4–60% V_2O_5 at 900 °C
40	Mudgal *et al.*,[59]	Superni 718	Cr_3C_2-NiCr + 0.2wt. %Zr and Cr_3C_2-NiCr	D-Gun spray process	40%Na_2SO_4 + 10%NaCl + 40%K_2SO_4 + 10%KCl. and 75%Na_2SO_4 + 25% NaCl.
41	Mudgal *et al.*,[60]	Superni 600	Cr_3C_2-25(NiCr) +0.4 %CeO_2 and Cr_3C_2-25(NiCr)	D-gun technique	Na_2SO_4-25%NaCl
42	Mudgal *et al.*,[61]	Superni 600, Superni 718, and Superni 605	-	-	Na_2SO_4–25%NaCl) at 900 °C
43	Ahuja *et al.*,[62]	Superni 718, Superni 600 and Superco 605	Cr_3C_2-(NiCr)-0.2 wt% of Zr	D-gun technique	40%Na_2SO_4-40%K_2SO_4-10%NaCl-10%KCl at 900 °C
44	Goyal *et al.*,[63]	T22	CNT+Cr_3C_2–20NiCr	HVOF technique	In zone of super-heater zone in actual environment of boiler of a thermal power plant at 900°C
45	Sidhu *et al.*,[64]	T22	93($WCCr_3C_2$)-7Ni and 83WC-17Co coatings	HVOF technique	In coal fired boiler environment of 900°C in superheater zone.
46	Sidhu *et al.*,[65]	T91	83WC-17Co, 86WC -10Co-4Cr, 93(WC-Cr_3C_2)-7Ni, 75Cr_3C_2-25NiCr,	HVOF Technique	In actual boiler environment at an elevated temperature of 900◦C in superheater
47	Goyal *et al.*,[66]	ASTM-SA2 13-T22	Cr_2O_3–CNT	HVOF technique	In a molten salt environment of Na_2SO_4+60wt %V_2O_5 salt at 700°C.
48	Goyal *et al.*,[67]	ASTM-SA2 13-T22	Cr_2O_3 + 1, 2, 4, 6, and 8 wt-% of CNT	HVOF Technicque	In real power plant boiler environment at high temperature of 900°C.

The following outcomes were discussed in these studies:

Reddy *et al.*,[20] stated that Cr_2O_3 has less solubility in highly acidic molten salt mixture of Na_2SO_4-60%V_2O_5. According to their study, the presence of chromium oxide formed around the Cobalt and Nickel-rich splats present in the pores could have acted as barriers against the penetration and diffusion of corrosive species, blocking their passages. Dolekar *et al.*,[21] demonstrated that, in comparison to the conventional YSZ TBC system, the YSZ/$Gd_2Zr_2O_7$ layer demonstrated better performance in terms of hot corrosion and oxidation. This was due to the pre-sacrificial layer of $Gd_2Zr_2O_7$ in YSZ/$Gd_2Zr_2O_7$ content, which lessen the damage to the YSZ layer. Singh *et al.*,[22] in their paper, defined that the subsurface inter-splats in the composite coating of Ni-22Cr-10Al-1Y-SiC (N) deposited on T22 by HVOF process exhibited favourable results against hot corrosion due to the presence of SiO_2. In another study, Singh *et al.*,[23] arrived at the

conclusion of the formation of silicon dioxide accompanied by oxides of Nickle, Aluminium, and Chromium which have proved to be more resistive to corrosion than the formation of B_2O_3 with these oxides. Singh *et al*.,[24 25]concluded that the use of nano coatings provided greater protection compared to micro coatings. This is due to the formation of oxides of boron resulting from the full melting of nano particles of boron carbide within the inner splats, in combination with oxides of chromium, nickel, aluminum, and a nickel/chromium spinel. Lone *et al*.,[26] revealed that cerium concentration in the cerium oxide-coated Superni-75 samples increases when the weight variation per unit area decreases. The conclusion drawn was that the presence of a cerium oxide layer on the surface impedes the movement of ions by reducing their short circuit diffusion. Bala *et al*.[27] and Mittal *et al*.,[28] found that the uncoated steels experienced severe spallation in the form of oxide scales, likely due to the formation of unprotective Fe_2O_3 oxide scales. In contrast, the Ni-50Cr coated steels exhibited reduced weight gains and maintained their oxide scales until the end of the experiment. The studies also revealed that the protective oxides present on the coated specimens mainly comprised of Chromium and Nickle, as well as their spinel. Nithin *et al*.,[29] concluded that CoCrAlY + Al_2O_3 + YSZ (C1) has effective resistance to corrosion than CoCrAlY + CeO_2 (C2) deposited on boiler steels, because of the formation of thermodynamically stable α-Al_2O_3 in C1 and outward growth of superficial irregular cracks $CeVO_4$ in C2. Singh *et al*.,[32] indicated that Ni–20Cr– TiC–Re coating offered the better corrosion resistance among different coatings of Ni–20Cr, Ni–20Cr–TiC. Jafari and Sadeghi[33] and Sadeghimeresht *et al*.,[34] found that KCl can cause significant corrosion to coatings that contain chromium, due to frequent chlorination-oxidation processes that destroy the protective chromium layer and lead to the loss of Cr through the formation of chromate. Eklund *et al*.,[35] concluded that NiAl coating exhibited excellent resistance to corrosion and effectively blocked the diffusion of all corrosive substances, including chlorine and oxygen, through the coating. Sundaresan *et al*.,[36] concluded that detonation sprayed coatings performed better than plasma sprayed coating. In a study, Singh *et al*.,[38] revealed that TiO_2 functions as a protective barrier against corroding agents by occupying any gaps or fractures in the coating's microstructure. Wang *et al*.,[39] found that NiCrB coatings have greater corrosion resistance in comparison to NiCrTi coatings as a result of boron's inclination towards producing small oxide particles, ultimately augmenting the safeguarding of oxide layers. Abu-warada *et al*.,[40] showed that the presence of a stable Al_2O_3 oxide scale on the CoNiCrAlY coating reduced chloride penetration and prevented the degradation of the protective oxide scale through the formation of chromates. Bhatia *et al*.,[41] indicated that Mo and Nb exhibited a proclivity for outward diffusion from the substrate to the coating. Zhou *et al*.,[43] indicated that the incorporation of multiple alloying elements into the Cr_3C_2-NiCrMoNbAl coating led to a significant reduction in the corrosion rate compared to the Cr_3C_2-NiCr coating. Bala *et al*.,[44] revealed higher microhardness of the Ni-50Cr coating than Ni-20Cr was identified as the reason behind better resistance to oxidation and erosion. Sadeghi and Joshi[45] found that the HVAF coating showed better high-temperature corrosion as compared to HVOF coating due to the formation of slightly denser protective oxides. A significant finding of the study was that the lower hardness of the HVOF coating, as compared to the HVAF coating, resulted in more substantial removal of the former during the erosion test, due to the impact of particles on the coating. Kaushal *et al*.,[48] highlighted that the denser structure of the D-gun sprayed coating provided superior corrosion resistance in comparison to the cold spray and HVOF spray coatings. Kai *et al*.[49] showed that the nanostructured NiCrC coating facilitated an increased rate of grain boundary diffusion, leading to the development of a denser oxide scale with a higher growth rate. This helped to stop the depletion of chromium at the substrate/scale interface. Rani *et al*.,[53] revealed that by utilizing the detonation gun coating technique, a uniform and strongly adherent coating with a dense microstructure was achieved. Thakare *et al*.,[54] suggested that the creation of Cr_3C_2 could be attributed to the enhancement of the steel substrate's corrosion resistance. Abu-warda *et al*.,[56] found that the NiCr coatings tend to protect the substrate but undergo severe corrosion attacks by the chlorides. In addition to it, the formation of potassium chromate and penetration of chlorides as major causes of the attack. Matikainen *et al*.,[57] discussed the benefits of using HVAF, such as the formation of more durable coatings with improved toughness and a more uniform coating structure. This is attributed to the higher particle velocities and

temperature control achieved during the HVAF process. Chatha *et al*.,[58] revealed that the pores in the Cr_3C_2–NiCr coating became blocked due to the rapid formation of oxides at the boundaries of the coating splats and within the open pores during heat treatment. This prevented corrosive substances from flowing inward towards the substrate. Mudgal *et al*.,[59] concluded that the presence of Cr_2O_3 on the surface may be the reason behind corrosion resistance against the aggressive surroundings on Cr_3C_2-(NiCr) coating and the splat boundaries. During corrosion, the inclusion of Zr in the coating powder led to a decrease in the oxidation rate and enhanced the ability of the oxide scale to adhere to the surface of the coating. Mudgal *et al*.,[60] conducted concluded that Cr_3C_2-25(NiCr)+0.4%CeO_2 coating consists CeS on the surface scale and CeO_2 along the splat boundaries other than Cr_2O_3 and spinels, The presence of CeO_2 at the splat boundaries restricted the flow of reacting species which decreses the corrosion rate. Mudgal *et al*.,[61] pointed out that the Co-based alloy experienced a greater increase in weight compared to the Ni-based alloy because the scale on the Co-based alloy was not protective in nature. Ahuja *et al*.,[62] concluded that the substrate of Superni 600 and Superni 718 displayed the formation of a thick and dense oxide scale, whereas the corroded coated substrate of Superco 605 showed porous and loose oxide. Goyal *et al*.,[63] noticed the lowest corrosion rate with value of 28.49 mpy was observed for Cr_3C_2–20NiCr -2 wt-%CNT coating on T22 steel. Sidhu *et al*.,[64] listed the performance of coating in the order of 83WC-17Co coated T91 <83WC-17Co-coated T22 < 93(WC-Cr_3C_2)-7Ni coated T22 < 93(WC-Cr_3C_2)-7Ni-coated T91. In another study, Sidhu *et al*.,[65] found that the presence of a thin layer of tungsten carbides, nickel oxides and chromium oxides is responsible for the coating performance on steel alloys made up of 93% WC-Cr_3C_2 and 7% Ni.. Goyal *et al*.,[66 67] found that even distribution of CNTs within the coating matrix and In addition to it, the protective nature of chromium oxides found on the surface scale exhibited superior corrosion resistance.

Conclusions

Researchers have reached the conclusion that various thermal spray coating processes can easily coat any material onto a substrate material, such as boiler steels. Among different thermal spray techniques. With its advanced and effective capabilities, the HVOF process is increasingly being used to produce high-quality coatings that exhibit high micro-hardness and low porosity. Surface modification techniques are crucial in various industries to avoid boiler failures. These techniques enhance the durability of machine parts, leading to longer lifespan and reduced replacement expenses. This results in high thickness coatings that are dense, strongly adhered to the material of substrate, and exhibit significantly greater micro-hardness as compared to the base steels. The valuable insights presented by this study can aid in selecting the optimal coating method and combination to prevent failure of boiler steels.

Acknowledgement

The authors thank Paramjit Singh, GM Power Plant, Nectar Lifesciences Ltd., Derabassi, Punjab, India for his valuable suggestions.

Funding

The research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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