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Review Article

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A Review of High-temperature Oxidation Behaviour of Thermally Sprayed Boiler Tube Materials in Advanced Coal-fired Thermal Power Plants

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Abstract

Coal-fired thermal power plants are the prime source of electricity worldwide. The higher operating temperature and pressure of these power plants cause high-temperature oxidation and corrosion of the boiler materials used in these power plants. Various advanced materials have been developed to resist these degradations, but individual advanced materials were found insufficient to resist such degradations for longer. It is accomplished by providing an additional protective coating of the oxidation-resistant material over the surface of the metallic component having desired mechanical properties. Researchers have investigated the high-temperature performances of various base materials and coatings combinations. Different coating techniques have been used to deposit the coatings, including electroplating, thermal spray coating, physical vapor deposition, chemical vapor deposition, etc. Among all these methods, the thermal spray technique is reported to be a cost-effective method to deposit coatings with good mechanical and microstructural properties. In this paper, a brief review of the literature on the high-temperature oxidation performance of thermally sprayed boiler tube materials has been presented and discussed.

Keywords

High-temperature oxidation, Degradations, Thermal spray coating

Introduction

Coal is the primary source of electricity generation [1]. Although the world is focusing on renewable energy resources for electricity generation, coal-fired thermal power plants share the major electricity production. Hence, it is essential to address the problems associated with material failures in existing coal-fired thermal power plants. Many coal-based power plants are modified into advanced, supercritical, and ultra-supercritical coal-fired thermal power plants to overcome the low thermal efficiency and high pollutant emission from burning fossil fuels [2]. Advanced coal-fired thermal power plants are categorized, in table 1, based on their temperature and pressure range [3-5].

The higher operating temperature of modern power plants causes high-temperature oxidation of the boiler materials [6, 7]. Figure 1 shows the high-temperature oxidation mechanism of boiler tube steels. The outward diffusion of metal ions (M^{n+}) and the inward surface adsorption of oxide ions occur at higher operating temperatures in advanced power plants. The oxide ions then react with the metal ions to produce metal oxides at the surface of the boiler material. With the increase of oxide thickness, porosity and micro-cracks develop over time, causing spallation or delamination of these oxide scales. The high-temperature oxidation decreases the life of metallic components, which is mainly responsible for early repair or replacement of the boiler tube materials, thus increasing the plant's maintenance costs [8].

Table 1: Temperature and pressure range of different power plants [3-5].

Type of power plant	Main steam pressure, MPa	Main steam temperature, °C	Average efficiency
Subcritical	<22	<565	35 - 40
Supercritical	22 - 25	540 - 580	40 - 45
Ultra-Supercritical	25 - 30	580 - 620	45 - 50
Advance Ultra-Supercritical	30 - 35	620 - 700	>50

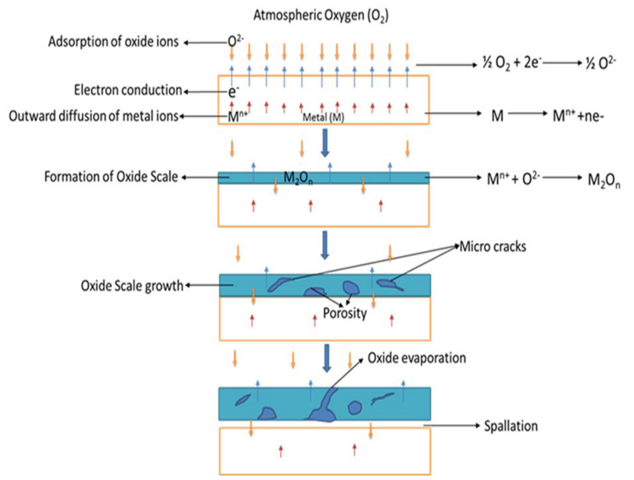

Figure 1: High temperature oxidation mechanism.

Various methods have been used to reduce the high-temperature oxidation of boiler materials in advanced coal-fired power plants [9]. Among these, the development of oxidation-resistant coatings over the surface of the boiler material is widespread [10]. There are various techniques to deposit the coatings over the material surfaces, among which thermal spraying finds a broad scope as it provides a coating with good mechanical and microstructural properties [11]. This work presents a comprehensive review of studies on the oxidation behaviour of thermal spray coatings over different boiler materials at high temperatures, which may help select the suitable material or coating technique in preventing materials against harsh industrial environments.

Materials and Methods

Steel is the most common material used in advanced thermal power plants to make water walls, superheaters and reheater tubes, turbine blades, etc. [12, 13]. Different materials have been developed over the last few decades, supporting the installation of advanced supercritical and ultra-supercritical power plants globally [4, 5]. Some important boiler materials, oxidation-resistant coatings and various thermal spray coating deposition techniques are discussed here.

Boiler tube steels

Materials used in advanced coal-fired thermal power plants should have high creep strength and oxidation resistance to withstand the high temperature and pressure conditions of power plants [14]. Various elements (Cr, Ni, W, V, Nb, Mo, etc.) are added to boiler steels to enhance their properties like creep strength, oxidation resistance, corrosion resistance, etc. [15, 16]. The chemical compositions of some of the widely used boiler steels of the advanced thermal power plants are presented in table 2.

Table 2: Some commonly used boiler steels in modern power plants [3-5].

Composition (%)/ materials grade	AISI 316	AISI 410	T22	T91	T92	Super 304H	IN740
C	0.08	0.15	0.05 - 0.15	0.07 - 0.14	0.07 - 0.13	0.04 - 0.1	0.03
Cr	16 - 18	11 - 13	1.9 - 2.6	8 - 9.5	8.5 - 9.5	18 - 20	25.0
Ni	11 - 14	0.75	-	≤0.4	≤0.4	8 - 11	49.5
Mn	2.0	1.0	0.3 - 0.6	0.3 - 0.6	0.3 - 0.6	2.0	0.3
P	0.04	0.04	0.025	≤0.02	≤0.02	0.045	0.002
S	0.03	0.03	0.025	≤0.01	≤0.01	0.03	0.002
Si	0.75	1.0	≤0.5	0.2 - 0.5	0.2 - 0.5	0.75	0.5
B	-	-	-	-	0.001 - 0.006	0.001 - 0.01	0.002
Cu	-	-	-	-	-	2.5 - 3.5	≤0.1
Al	-	-	-	0.02	≤0.04	0.003 - 0.03	0.9
Ti	-	-	-	≤0.01	-	-	1.8
W	-	-	-	-	1.5 - 2.0	-	-
V	-	-	-	0.18 - 0.25	0.15 - 0.25	-	-
Mo	2-3	-	0.87 - 1.13	0.85 - 1.05	0.3 - 0.6	-	-
Co	-	-	-	-	-	-	20
Nb	-	-	-	0.06 - 0.1	0.04 - 0.09	0.3 - 0.6	2.0
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.	0.7

Oxidation resistant coating materials

Researchers worldwide have investigated various coating combinations [17-21]. According to the literature [22-24], alloying Ni-Cr-based composite coatings with Al, Y, Si, B, etc., increases their resistance to high-temperature oxidation. It has been reported that the formation of the Cr_2O_3 oxide layer is primarily responsible in protecting the material's surface against high-temperature oxidation [25-27].

Figure 2 presents the effectiveness of the various coating combinations against high-temperature oxidation. Many researchers have conducted cyclic oxidation tests of coating mate-

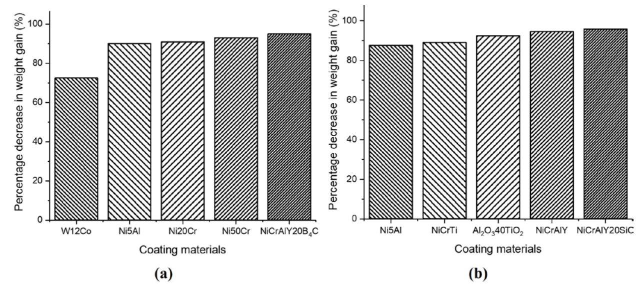

Figure 2: Oxidation behaviour of different coatings deposited over **(a)** T22 and **(b)** T91 boiler steel [18-20, 28-31].

Table 3: Some important literature related to the high-temperature oxidation behavior of thermally sprayed boiler tube materials.

Author	Substrate material	Coating material	Coating techniques	Results	Phases identified
Bala et al. [18, 21]	T22 boiler tube steel	Ni-20Cr, Ni-50Cr	Cold spray	After conducting the thermal cycling test for 50 cycles at 900 °C, the authors concluded that the cold-sprayed specimens provide better oxidation resistance.	The formation of chromium and nickel oxides are mainly responsible for the better oxidation resistance of the coated specimens.
Abu-Warda et al. [37]	T24 boiler steel	Ni20Cr	HVOF	The coated sample shows better resistance to oxidation at elevated temperatures.	Better resistance to oxidation at elevated temperatures was due to the protective oxide layers of Cr_2O_3 and $NiCr_2O_4$.
Kumar et al. [28]	T22 boiler steel	WC-12Co, Ni-20Cr	Detonation Gun spray	After 50 hours of the test at 900 °C, it was found that the Ni-20Cr coated samples are superior against high-temperature oxidation among all the samples.	According to XRD analysis Cr_2O_3 and $NiCr_2O_4$ protective oxide layers are responsible for the protection of the coated specimens.
Kumar et al. [29, 38] and Sharma et al. [30]	T22, T91, and SA516 boiler steel	Ni20Cr, NiCrTi, Ni5Al	Wire arc spray	After conducting the thermal cycling test for 50 cycles at 900 °C, it was concluded that among all the coatings, Ni20Cr coated SA516 samples and NiCrTi coated T91 samples show the maximum oxidation resistance. In contrast, Ni5Al coated T22 samples show the least oxidation resistance.	Ni, Cr, and Al Oxides were mainly responsible for the protection of the coated boiler steels. In NiCrTi coatings, Ti peaks were also revealed by XRD analysis.
Kumar et al. [39] and Singh et al. [19]	SA516 and T22 boiler tube steels	Ni20Cr, NiCrAlY-B_4C	Cold spray and HVOF sprayz	After conducting the thermal cycling test for 50 cycles at 900 °C, it was concluded that the nanocomposite coatings are more effective against high-temperature oxidation than micro composite coatings.	NiO, Cr_2O_3, Al_2O_3, $NiCr_2O_4$, $NiAl_2O_4$, and Al_3BC phases were found in XRD analysis which was responsible for the protection of coated specimens.
Kaushal et al. [40]	T22 boiler steel	Ni20Cr, Ni20Cr1Zr	HVOF	After 50 hours of the test at 900 °C, it was found that the Ni-20Cr1Zr deposited specimen was superior among all the samples.	NiO, Fe_2O_3, and $NiCr_2O_4$ phases were detected in XRD analysis.
Mittal et al. [41]	T91 boiler tube steel	Ni-Cr, Stellite-21	Detonation Gun spray	After 100 hours of the test at 900 °C, it was found that stellite-21 coated T91 boiler tube steel shows the maximum oxidation resistance among all the samples.	EDS analysis revealed the formation of Cr_2O_3, SiO_2, and Fe_2O_3 scales over coated specimens.
Singh et al. [20, 24]	T91 boiler tube steel	NiCrAlY, NiCrAlY-20SiC	HVOF	After 50 hours of testing at 900 °C, it was found that uncoated specimens show the least oxidation resistance due to the spallation of Fe_2O_3 oxide layers. NiCrAlY-20SiC coated specimens show better oxidation resistance among all the coatings.	XRD and EDS analysis revealed that the protective oxides of Ni, Cr, and Al are responsible for the coated samples' better oxidation resistance.
Sidhu and Prakash [42-44]	GrA1, T11, and T22 boiler tube steel	NiCrAlY, Ni20Cr, Ni3Al, Stellite-6	Plasma spray	After 50 hours of tests at 900 °C, it was found that plasma sprayed GrA1 steel shows the maximum oxidation resistance compared to other coated steels. Stellite-6 coatings are superior among all the coatings, followed by Ni_3Al coatings.	Oxides of Ni, Cr, Al, and Fe were detected by XRD analysis which was responsible for the protection of the coated steels.

Singh et al. [17]	T22 boiler tube steel	Cr3C2-25NiCr, Cr_3C_2-25NiCr +25%(WC-Co)	HVOF	After 50 hrs of the test at 700 °C, it was found that the Cr_3C_2-25NiCr + 25% (WC-Co) coating samples are superior against high-temperature oxidation among all the samples.	Cr_2O_3, $NiWO_4$, and $NiCr_2O_4$ phases were detected by XRD analysis.
Kaur et al. [45, 46]	AISI 347H and T22 steel	Cr_3C_2-NiCr	HVOF	After 50 hours of testing at 700 °C, it was found that the coated specimens provided better oxidation resistance than bare specimens.	Cr_2O_3, Cr_7C_3, and Cr_2C phases were detected by XRD analysis.
Somasun-da-ram et al. [47]	T22, MDN-310, Superfer 800H boiler steel	Cr_3C_2-35% NiCr-5% Si	HVOF	After 50 hours of the test at 700 °C, it was found that the coated specimens performed better than the uncoated specimens.	Oxides of Cr, Ni, and Si were detected by XRD analysis.
Sharma et al. [48]	AISI 1020 carbon steel	Al_2O_3, Al_2O_3-SiC	Detonation Gun spray	After testing for 50 cycles in a muffle furnace, at 900 °C, it was concluded that Al_2O_3-3 wt. % SiC coated samples have greater oxidation resistance between the two coated samples.	α-Al_2O_3, γ-Al_2O_3, and SiC phases were observed in XRD and EDS analysis.
Ansari et al. [31]	T-91, A-1 boiler steel, Superfer800H	Al_2O_3-40% TiO_2	Plasma spray	After 50 hours of the test at 900 °C, it was concluded that among all the samples, Al_2O_3-40%TiO_2 coated A-1 boiler steels show maximum oxidation resistance, while Al_2O_3-40%TiO_2 coated T91 samples show the least oxidation resistance.	Al_2O_3, TiO_2, Cr_2O_3, $Al_2Ti_7O_{15}$, and $NiCr_2O_4$ phases were detected in XRD analysis.
Goyal et al. [49]	T11 boiler tube steel	Al_2O_3, Al_2O_3-CNT	Plasma spray	After 50 hours of the test at 900 °C, it was found that Al_2O_3-CNT coated T11 boiler tube steel performs better than Al_2O_3 coated T11 and uncoated T11 boiler tube steel.	XRD and EDS analysis revealed the formation of Al_2O_3 and Fe_2O_3 phases.
Kamal et al. [50] and Sidhu et al. [51]	Superni 75, Superni 718, Superfer 800H	Cr_3C_2-NiCr, WC-Ni CrFeSiB	Detonation gun spray, HVOF	After the cyclic oxidation test of 100 hours and 50 hours at 900 °C and 800 °C respectively, it was found that Cr_3C_2-NiCr and WC-NiCrFeSiB coated Superni 75 show the maximum oxidation resistance among all the samples.	XRD and EDS analysis revealed the formation of Cr_2O_3, NiO, NiC, Fe_2O_3, Cr_3C_2, Cr_7C_3, $Cr_{23}C_6$, and $NiCr_2O_4$ phases.

rials over T22 and T91 boiler tubes steels at 900 °C for 50 cycles [18-20, 28-31]. Authors have experimentally analyzed different coating combinations to compare the weight gain of the coated material against the uncoated material. High-temperature oxidation causes weight gain of the material, so the coating combination having the lowest weight gain is the most effective. Figure 2a indicates that the NiCrAlY20B$_4$C coating provides the maximum resistance to high-temperature oxidation, while W12Co coatings provide the least resistance to oxidation. Similarly, from figure 2b, it can be concluded that the NiCrAlY20SiC coating has the maximum resistance, while Ni_5Al coating has the least resistance to high-temperature oxidation.

Thermal spraying methods

Thermal spraying is an efficient method to develop a coating over the surface of boiler material [32, 33]. It creates a coating by striking the fully or partially melted coating powders over the surface of the substrate materials with high velocity [34]. Some important thermal spraying methods are plasma spray, detonation gun spray, high-velocity oxy-fuel spray and cold spray [9, 34]. These processes have merits and demerits and are used depending on their applicability and requirements [35].

High-temperature Oxidation Behaviour of Thermally Sprayed Boiler Tube Materials

A single material cannot fulfil all the requirements of advanced thermal power plants. Material properties can be improved by adding an extra protective layer on the surface of the base material [36]. Some vital research works on the oxidation behaviour of thermally sprayed boiler tube materials are presented and discussed in table 3.

Discussion

Various thermally sprayed coatings such as Ni2Cr, NiCrAlY, WC-Co, NiCrTi, NiCrAlY-B$_4$C, Stellite-21, Stellite-6, Cr_3C_2-NiCr, Al_2O_3, etc. have been investigated by the researchers to resist the high- temperature oxidation of the boiler tube materials. Different thermal spray coatings methods, such as high velocity oxy-fuel, wire arc spray, plasma spray, detonation gun spray, etc., have been used to enhance the microstructural and mechanical properties of the boiler tube materials. Isothermal and cyclic oxidation studies show that the thermally sprayed coatings protected the boiler tube materials from high-temperature oxidation. The researchers have used various material characterization methods to analyze the high-temperature oxidation behaviour of the coated and uncoated specimens. Microstructural examinations conducted by various researchers showed the presence of non-protective Fe_2O_3 oxide over the surface of uncoated materials, which is responsible for the loss of the material through delamination and spallation of the oxide layer. On the other hand, various protective oxide phases such as Cr_2O_3, NiO, Al_2O_3, SiO_2, TiO_2, Cr_3C_2, Cr_2C, Cr_7C_3, $NiCr_2O_4$, $NiAl_2O_4$, etc., were detected on the coated specimens, which were responsible for the protection of the boiler tube materials form high-temperature oxidation.

Conclusion

After a comprehensive study of different research conducted, it can be concluded that the thermally spray coatings are very effective for protecting boiler tube materials against the high-temperature oxidation environment of advanced coal-fired thermal power plants. According to literature reviews, the most commonly used oxidation-resistant coating materials are Ni-Cr, NiCrTi, Ni-Al, NiCrAlY, NiCrAlY-B_4C, NiCrAlY-SiC, Cr_3C_2-NiCr, Al_2O_3-SiC, Al_2O_3-TiO_2, WC-Co, etc. According to many works of literature, SEM, EDS, and XRD analysis revealed that the formation of protective oxides of various elements (NiO, Cr_2O_3, Cr_3C_2, Al_2O_3, Fe_2O_3, etc.) at higher temperatures is mainly responsible for protection against high-temperature oxidation.

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Conflict of Interest

There is no conflict of interest.

Credit Author Statement

All the authors contributed equally. All the authors read and approved the manuscript.

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