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Application of high velocity oxy-fuel technique to combat surface degradation in power generation industry – a review

The high temperature corrosion and wear of steels in coal based power plant at elevated temperature is the primary reason behind downtime in power generating plants. The failure of steel components is big hazard to the effectiveness of the power-plant and responsible for the economic loss. To counter the effect of environmental degradation on steels, the chemical composition has been improved and their microstructures are also modified. But these changes have provided limited protection to the steels. The other useful method to control the degradation of steels is to apply coating of the protective material on the surface of target metal with the help of thermal spray technology. In this article, a systematic study of literature has been done to understand the level of protection provided by the HVOF (thermal spray technique) sprayed coatings to the different steels employed in degrading environments in coal based power plant. This article may help to researchers to select the HVOF technique with best coating combination to resist the failure of steels in coal based power plants.

Keywords: Corrosion, wear, HVOF, steel, surface, thermal spray, etc.

1.0 Introduction

The Asia-Pacific region has the highest consumption of natural resources for electricity generation among the other regions of the world. Out of which, the 58% of its fuel requirements are fulfilled by the coal alone. India reported 72% dependency on coal for its electricity generation in 2021(BP, 2020). The overall economic losses in the coal based power plants associated with corrosion/oxidation-erosion based degradations are very high in India. The presence of moisture, ash particles, salts and acids formed after the chemical reaction of the exhaust gases are found responsible for high temperature corrosion of metal elements (Raask, 1985; Sequoia et al., 1969). The heating of steel surfaces in the presence of oxygen/air results into oxidation which degrades the metal surface by generating thick scales of metal oxides. The presence of unwanted hard dust particles such as sand particles, quartz, pyrites, clay, etc. causes the high temperature erosion (Levy, 1990; Raask, 1969; Simms et al., 2007).

There is a need of procedures to minimize the maintenance costs and extend the life of existing machinery in coal based power plants.

There are many techniques by which surface under degradations can be modified to resist to corrosion and wear (Natesan, 1993; Nava and Henry, 2003; Wood and Wharton, 2011). The metallic surface can be thermally/mechanically treated to modify its microstructure or the coatings of protective layers can be deposited by the appropriate technique.

In the present study, the literature review of the studies has related to the corrosion and wear resistant performance of the coatings deposited by the high velocity oxy-fuel techniques has been done. There is a wide variety of boiler steels employed at different location of the coal power plant, in the form of machinery such as boilers, reheaters, economizers, superheaters, transportation ducts, draft fans, gates, valves and other structures (Dhand et al., 2021). These steels undergo mild to severe surface degradations at moderate and high temperature operating conditions. It will be interesting to study and understand the extent of application and level of protection provide to the steels by the HVOF coatings in the degrading environments.

2.0 Materials

The formulation and selection of steel for specific uses depends on the material specification requirements, usually long-term durability at above-threshold operating temperatures and pressures. The properties which are required in materials under such conditions include high creep strength, thermal fatigue strength, microstructural stability, etc. The different types of steels employed in coal based power plants at various locations are mentioned in Fig.1 and Table.1.

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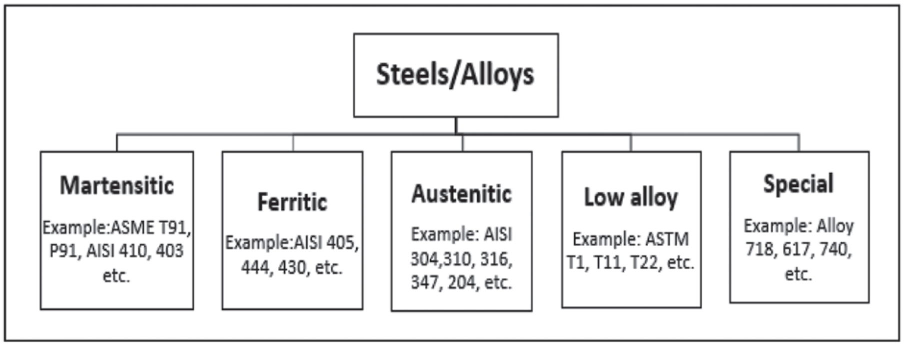

Fig.1: Different kinds of steel used in coal based power plants

TABLE 1: APPLICATION OF DIFFERENT TYPES OF STEEL AT DIFFERENT LOCATIONS IN COAL BASED POWER PLANTS

Material	Application
AISI 304	Springs, Nut, Bolts, Screw, tubes, gates, etc. used at high temperatures.
AISI 316	In boilers, structures, guide plates, transfer ducts, and other corrosion resistance applications at moderate and high temperatures.
AISI 310, 347	High-temperature conditions for oxidation resistance properties such as structure plates, tubes, etc.
AISI 405, 430	Circulation ducts of pressurized steam due to good creep strength.
AISI 410	High strength and fatigue resistance applications such as turbines, guide vanes, flow controllers, etc.
T91	In tubes of superheaters in ultra-high-temperature applications
T11, T12	For tubes in reheaters, economizers, etc.
Alloy 718, 600, 625	To perform in high to very high-temperature applications in oxidizing and corroding environments in tubes, superheaters etc.

The low-alloy steels based on 2.25Cr–Mo steel (such as T11, T22, T1, etc.) improved by the addition of V, Ti, Nb, B, W, etc. chemical elements can withstand the operating temperatures up to 550°C. The martensitic steels composed of 9% Cr-MoV (such as T/P91, T/P92, etc.) can withstand temperatures up to 600°C and are mainly used in super-heater tubes and coils. The ferritic steels such as AISI 405, 444, 430, etc. are used in power generation industry due to its high formability, corrosion resistance and less cracking as compared to austenitic steels. The austenitic steels (such as AISI 304, 316, 310, etc.) with an improved chemical composition and microstructure are used oxidation and corrosion resistance environment of the temperature range 560–700°C, mainly in boilers tubes, supply pipes, and turbine regulator valves etc. The ferrous and nickel based special steels such as alloy 718, 740, 600, etc. are specially designed materials for extremely high temperature working conditions. These steels do not undergo oxidation and corrosion easily at temperatures above 1000°C and provide high structural stability to the metallic components.

3.0 Modes of degradation

The Fig.2 shows the different modes of surface degradations in steel components in coal based power plants.

3.1 CORROSION/OXIDATION

In coal fired power plants, the exhaust gases from the burning of fuel consist of chemicals such as sulphur, chlorine, and alkali compounds. These chemicals at high temperature reacts with the metallic surfaces and causes serious corrosion problems. The chemicals such as HCl, SO_2, $CaCO_3$, etc. generated from coal combustion initiate the corrosion process. The corrosion taking place at high temperatures is two types i.e. hot corrosion types I and II:

Fig.2 Shows surface degradations of steel components in coal based power plants

1. Type I hot corrosion: The type I corrosion occurs at temperatures above 850°C (i.e. melting temperature of Na_2SO_4) (Dhand et al., 2021; Nava and Henry, 2003). The alkali compounds such as metal sulphates, carbonates, and acetate etc. get condense on the surface of metallic elements exposed to high-temperatures. It chemically reacts with the protective oxide layer formed at elevated temperatures and dissolve it. These oxide layers are normally formed of chromium. After the removal of chromium oxide layer, the oxidation of the exposed surface takes place rapidly and degrades the material.
2. Type II hot corrosion: The type II corrosion takes place below 750°C temperature in the presence of H_2O, SO_2,

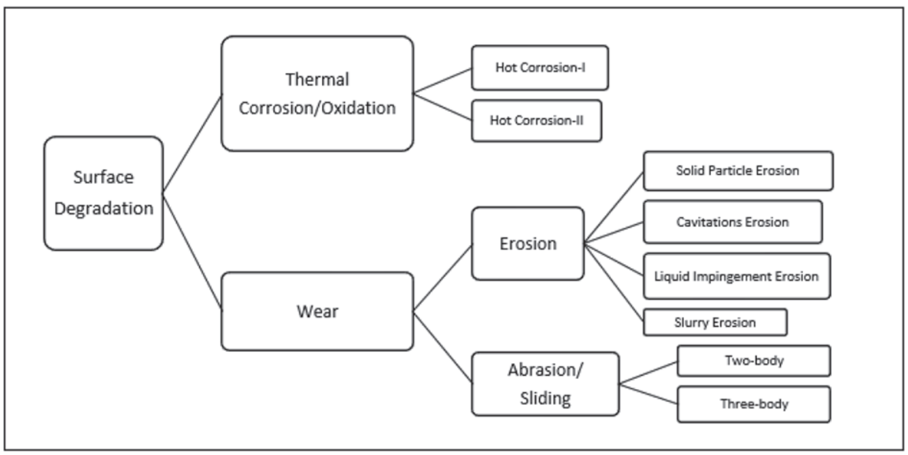

Fig.2: Surface degradations of steel components in coal based power plants

HNO_3, etc. During this type of corrosion, low melting point eutectic mixtures of K_2SO_4 and $CaCO_3$ cause pitting on the metal surface. It mainly occurs in moderate to high temperature applications (Masuyama, 2001).

Oxidation, is the form of corrosion in which weak oxide scales of Fe and Cr elements are formed at high temperatures in the presence of oxygen. This mechanism results into the material loss from the surface of the metallic components in the form of scales, as steels and its various constituents have high affinity for oxygen. The different steels allow diffusion of oxygen at different rates and hence represent slow or fast oxidation at elevated temperatures.

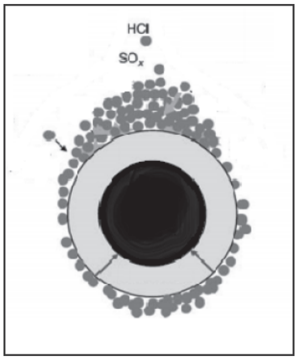

Fig.3: Schematic view representing corrosion causing elements on the tube surface of heat exchanger

3.2 Wear

It is the removal of the material from the steel surface due to the mechanical action of the counter body. The wear mechanism may combine the effects of micro-cutting, micro ploughing, plastic-deformation, cracking, fracture, etc. during the physical interaction between two counteracting materials: Abrasive wear takes place when hard material slides over the surface with relatively less hardness. If two bodies rubbed against each other than the material removal takes place mainly from the surface with less hardness due to friction. This type of wear is called two body wear. The other type of wear is caused by the debris or abrading particles trapped in between the two sliding surfaces, such type of abrasion is known as three body wear. The intermediate particles can be free or embedded into one of the abrading surfaces.

Erosion wear of metallic components is a common problem in coal fired power plants. During this, the hard dust particles such as quartz, sand, alumina etc. suspended in exhaust gases raising from the combustion of coal causes wear. This erosion by fly-ash and soot blower can lead to loss of material thickness and failures in tubes of economizers and reheaters. Such type of erosion is also known as solid particle erosion. The severity of erosion depends upon the flow velocity of eroding particles, the hardness of erodent particles and the target material, and the temperature conditions.

4.0 Combating the surface degradation

4.1 Techniques Available

There are different methods available for protection of the metallic surfaces from high temperature corrosion-oxidation and wear. These methods may involve application of protective coatings or surface treatment processes to improve the degrading resistance properties of the base metal. These techniques differ in their basic principles, ease of application and the range of protection which they provide after modification of the surface.

The surface treatment is based on the principle of modification of composition and/or microstructure of the target surfaces such as in shot peening, hardening, carburizing, etc. Whereas in the coating techniques, thin/thick layer of protective material is deposited on the base metal to be protected such as in thermal spray coatings, cladding, weld overlays, etc. The selection of surface modification technique depends on the target application and its desired properties such as hardness, friction coefficient, residual stresses, appearance, etc.

4.2 HVOF technique

Among various coating based surface modification techniques, the thermal spray coating techniques are widely used to deposit the protective material on degrading base

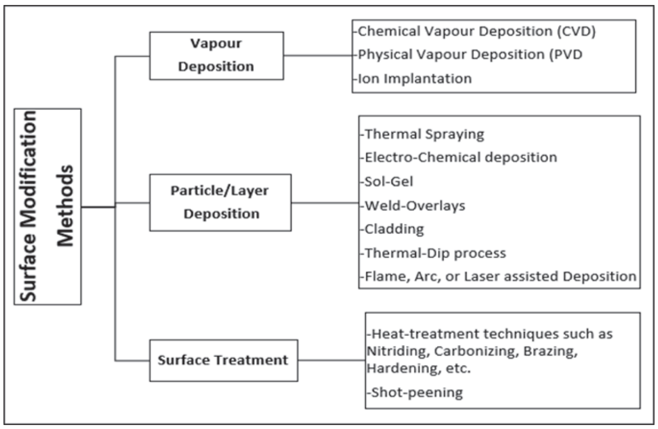

Fig.4: Various surface modification methods useful in resisting degradation of steels

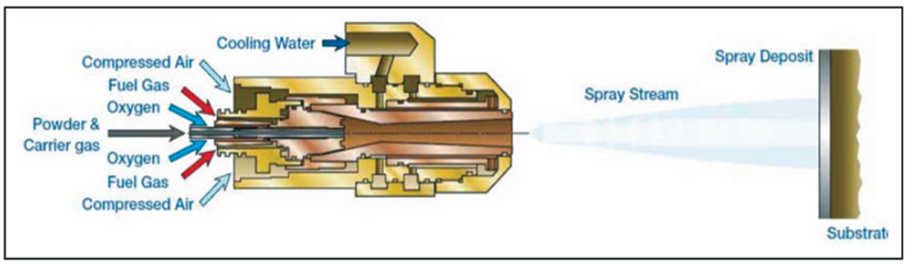

Fig.5: The schematic diagram of the HVOF spray system

Table 2: Studies done by various researchers to evaluate the performance of HVOF coatings on different steels in degradtion conditions

	Steel Grade	Coating material	Degrading environment	Findings	Ref
1	AISI 310	Cr_3C_2-NiCr	High temperature oxidation	• The coating was found intact with substrate surface while testing it for oxidation resistance at 900ºC. • The oxidation of coated sample was reported one-third of the value reported in uncoated steel sample. • The coatings represented splat and globular microstructure of high density.	(Shukla et al., 2015)
2	AISI 316	Cr_3C_2-NiCr	Sliding/abrasion wear	• The coating represented lamellar structure. • The wear rate of coatings varied proportionaly with the applied normal loads. • The pull-out of carbide particles and brittle fracture of coating were found dominant mechanisms.	(Vashishtha et al., 2018)
3	AISI 316	NiCrBSiFe	Sliding/abrasion wear	• The coating reflected better wear resistance against alumina material than silicon nitride. • The wear rate increased with the increase in load. • The abrasion wear, micro-cracks, and ploughing were found dominant.	(Rukhande et al., 2020)
4	T-91	Cr_3C_2-NiCr	High temperature corrosion	• The coating was tested for corrosion in molten salt environment of Na2SO4-60%V_2O_5 at 550ºC and 700ºC. • The coating was found highly effective in resisting the corrosion. • Some elements of the substrate diffused into the coatings i.e. Mo and Nb.	(Bhatia et al., 2014)
5	T-91	Ni-20Cr	High temperature oxidation	• The uncoated steel suffered severe oxidation attack. The oxide penetrated deep inside the substrate. • The coating was found effective in resisting the oxidation due to the formation of oxides of Cr and Ni at high temperatures.	(Chatha et al., 2013)
6	AISI 1070	WC-17Co	Sliding/abrasion wear	• The protective coating coverage is directly related to coefficient of friction and negatively related with the wear rate. • Continous cracking of coating and wear debris were reported during testing on tribometer.	(Katranidis et al., 2019)
7	AISI 304	Al_2O_3-NiAl	High temperature corrosion and wear	• The coatings successfully resisted the high temperature oxidation and wear upto 750ºC whereas the uncoated sample was severely oxidized. • No substrate degradation was observed even at 850ºC in the coated samples. • At high temperatures, the coating started degrading with generation of micro-cracks and delamination.	(Abu-warda et al., 2019)

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	Steel Grade	Coating material	Degrading environment	Findings	Ref
8	AISI 347	Ni-20Cr	High temperature erosion-corrosion	• The coating offered high resistance to oxide scale spallation during cyclic testing and shown good ahesive strength. • It was reported the coating is 85% more effective in resisting oxidation and 44% more effective in reducing mass loss, than the uncoated steel.	(Kaushal et al., 2011)
9	AISI 4340	Al_2O_3	Tribochemical performance	• The investigator studied the effect of HCl based corrosive environment on the sliding wear performance of alumina coating. • The coating started corroding above 10 % vol conc of HCl and the coating became unstable. • Adhesive wear mechanism was found dominant.	(Khosravifard et al., 2015)
10	AISI 4140	Ni based alloy (NiCrBSiWFeCoC)	Sliding/abrasion wear	• The wear resistance of uncoated sample was found half of that of coated samples. • The coefficient of friction value decreased with the increase in applied loads. • In uncoated samples the adhesive wear mechanism was found dominant and in coated samples, abrasive wear was responsible for degradation.	(Zheng et al., 2018)
11	AISI 304	Cr_3C_2-NiCr and WC-10Co-4Cr	High temperature Erosion and erosion-corrosion	• Both the coatings have high hardness than the substrate material. • Both the coatings exhibited poor erosion resistance at high temperatures and represented brittle material removal. • The erosion rates were high at normal impingement angles than at 30-degree angle.	(Kumar, 2015)
12	Superfer 800	Ni-5Al and NiCrAl	High temperature Corrosion	• The NiCrAl coating was better than Ni-5Al coating in resisting hot corrosion. • Thin oxide layer was observed on coated samples at 700°C after testing for 1000 h.	(Mahesh et al., 2010)
13	T-22	93(WC-Cr3C2)-7Ni, Cr3C2-NiCr, WC-17CO and 86WC-10CO-4Cr	Comparison of high temperature corrosion	• When all the coatings were tested for high temperature corrosion resistance under similar conditions at 900°C for 1000 hrs. The following sequence of corrosion resistance was observed:93(WC-Cr3C2)-7Ni > 86WC-10CO-4Cr > WC-17CO > Cr3C2-NiCr	(Singh Sidhu et al., 2017)
14	Super Co 605, MDN 121, and Ti-6Al-4V	Stellite-6, 10% Al_2O_3-90% CoCrAlTaY and 25% (Cr_3C_2-Ni-Cr)+75%NiCrAlY	Erosion wear	• The following sequence of erosion resistance was observed: Stellite-6 > 10%Al_2O_3-90% CoCrAlTaY > 25%(Cr_3C_2-Ni-Cr)-75%NiCrAlY	(Prasanna et al., 2018)
15	UNS-G41350 (Eq. AISI 4137)	Cr_3C_2–NiCr and WC–Ni	Erosion-corrosion	• The WC-Ni coatings reported least material loss due to erosion due to columnar microstructure. Whereas Cr_3C_2–NiCr represented lamellar microstructure.	(Espallargas et al., 2008)

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	Steel Grade	Coating material	Degrading environment	Findings	Ref
16	T-92	FeCrAl	High temperature Corrosion	• The coating performed best upto 700°C and suffered severe damage due to corrosion above this temperature when exposed for 1000h. • The oxide layers of Al and Cr were formed along with sulphidation attack, found during analysis.	(Hussain et al., 2015)
17	Austenitic steel (Gr. 253MA)	Cr_3C_2–NiCr	High temperature Erosion	• The coating was found effective in resisting erosion at the temperature range of 450-550°C.	(Matthews et al., 2009)

metals. These techniques use thermal energy generated electrically or chemically to melt the coating material and spray it under high velocities. The thermal spray techniques i.e. detonation spray, flame spray, arc-spray, plasma spray, HVOF spray etc. have difference of operating conditions, coating quality, range of depositing materials.

The high velocity oxy-fuel (HVOF) technique of thermal spray family has proved its strong candidature over the period of last few decades, to protect the steels at high temperatures in coal based power plant industry. The schematic diagram of the HVOF spray system is shown in Fig.5. The fuel gas and oxygen enter the gun separately where they are mixed and introduced into the combustion chamber. Powder to be deposited is injected either directly into the combustion zone or downstream in the nozzle by a carrier gas such as nitrogen or argon. The powder particles are heated and accelerated along the nozzle and at the spraying distance.

Gas flow rates and powder feed rates are controlled automatically. Due to the relatively high temperatures range i.e. 800-1200°C and very spray velocities, HVOF spraying produces high quality coatings particularly of such materials as carbides, metals and some composites. The high kinetic energy of the powder particles in HVOF spray process results in the deposition of high quality coatings. The cermet carbide based coatings developed during HVOF spraying have low porosity, low oxidation, high bond strength and deposition efficiency.

5.0 Studies related to the performance of HVOF coatings in various degrading environments

The Table 2 represents the wear resistance performance of the various HVOF sprayed protective coatings on different types of power plant steels.

6.0 Conclusions

1. The high temperature corrosion-erosion wear are serious causes of degradation and material loss in steels employed at various locations in coal based power plants. These degradations of metallic surfaces cannot be ignored but can be prevented with some advance surface modification techniques, to avoid any catastrophic failure. The selection of right protection technique is very important to get the desired level of protection.
2. The detailed study of literature represented the strong candidature of high velocity oxy-fuel (HVOF) technique to apply protective coatings on steels in coal power plants. The study has shown that the coatings deposited by HVOF technique succeeded in protecting the steels at high temperature corrosion, erosion and abrasion wear environments.
3. It was also observed that the HVOF sprayed coating of chromium with nickel and carbides are useful in protection against corrosion-erosion degradations and these coatings were found effective almost on every type of steel. Whereas the tungsten and nickel based coatings deposited by HVOF technique proved their worth in high temperature abrasion wear environments, by resisting the material loss due to wear. From the review of literature, it can be concluded that the coatings deposited by HVOF technique are effective in combating the surface degradations of steels in coal based power generation industry.

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