Erosion Corrosion Study of HVOF Sprayed Thermal Sprayed Coatings on Boiler Tubes: A Review

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Abstract

Many industrial parts used in power generation industries fail due to erosion, corrosion, and abrasion causes huge economic losses. These problems can be overcome by either changing the material or changing the environment or by separating the material surface from the corrosive environment. The distinct investigations have been carried out to overcome the erosion problems and observed that erosion resistant coatings have been gaining more importance in recent times. Among the different thermal spray coating techniques, High Velocity Oxy Fuel (HVOF) has emerged as an effective, advanced and rapidly developing process to produce dense coating at relatively low temp. with low porosity (less than 1%). HVOF has been widely adopted by many industries due to its several advantages such as high micro-hardness, adhesion strength, and erosion-corrosion and wear resistance, flexibility, and cost effectiveness with homogenous coating. The main purpose of this review paper is to review previous research in the field of high velocity Oxy-fuel (HVOF) sprayed coating, especially in context with Indian boiler tubes. In addition, an attempt has been made to study their basic principles, merits, demerits, applications and comparison.

Key words - High Velocity Oxy Fuel (HVOF), Boiler, Erosion and Corrosion.

1. INTRODUCTION

High temperature corrosion commonly known as hot corrosion is a severe problem in boiler tubes, fluidized bed combustion devices, gas turbines, I.C. engines, and industrial waste incinerators etc. [1]. Erosion - corrosion (E-C) alone has been reported to be responsible 50-75% of total arrest time in such devices and account for the multimillion dollar loss to the relevant industries [2]. In Indian coal fired boiler low grade coal is used as a fuel, which contains sulphur contents [3]. During combustion it produces SO₂, which is partly oxidized to Sulfur trioxide (SO₃). This SO₃ further reacts with sodium chloride (NaCl) and water vapour to give Na₂SO₄ (melting point 884°C), at combustion temperatures [4]. A small amount of vanadium (V) may also be present in coal, which on combustion forms Vanadium pentoxide (V₂O₅) having melting point 670°C. This may further react with Sodium sulfate (Na₂SO₄) to form sodium vanadates (Na₃VO) having a low melting point. These sodium vanadates (Na₃VO) are extremely corrosive to high temperature materials such as metal and alloy used in the combustion system [5-6]. Overall economic loss due to all the types of corrosion in India, accounts to US\$ 6500 million annually [7]. So, it is essential to understand the nature of various types of metal and alloy degradation to avoid their premature failures which ensure reliability and safety [8]. Thermal spray coating is a way of increasing the limits of use of materials for higher temperature applications like in boiler and gas turbine etc. [9] The coatings used at in such applications must be dense enough that any residual voids can be filled by formation of protective oxides and be thick enough to postpone the diffusion of corrosive species to the substrate material until protective oxides form within the coating [10]. There are many thermal spray techniques that can be used to deposit metallic coatings; however, thermal spray techniques such as flame spraying, arc spraying, plasma spraying, D-Gun, and HVOF spraying are extensively used for higher temperature application [11]. Among different thermal spraying techniques HVOF has emerged as an important sophisticated surface engineering tool to produce dense coatings with high micro hardness and adhesion values, and good erosion,

corrosion, and wear resistance properties [12]. HVOF coatings are homogeneous and dense as compared to the other types of thermal-sprayed coatings; nevertheless some residual oxides and porosity remain at splat boundaries [13]. This process was invented in the early 1980s by Browning and Witfield, while using rocket engine technologies. The process uses a combination of oxygen (O_2) with one of the fuel gases including hydrogen (H_2), propane (C_3H_8), propylene (C_3H_6), and even kerosene. Then the fuel (C_3H_6) and oxygen (O_2) are compressed into a combustion element/chamber in a regular flow, producing a jet of combustion products at extreme velocity. Powder particles (Ni / $Ni-20Cr$ / $Ni-5Al$, etc) injected into this gas stream are swiftly to a extreme velocity. Fusion is attained by the kinetic energy impact of the coating particles not by their elevated temperature: the HVOF process is done in an atmospheric environment. The flame temperature changes from 2500 °C to 3200 °C, depending on the fuel, the fuel gas/ oxygen ratio and the gas pressure [14]

Fig. 2.21 Schematic diagram of the HVOF process [15].

A) Merits & Demerits:

The main advantages of this process is lower porosity (<1%) because of higher particle impact velocities, higher bond strength (>80Mpa), smoother spray surface due to more impact velocities and smaller powder sizes, higher wear resistance because of tougher, harder coatings upto 1400 Hv, dense, and thick coating due to less residual stresses [16-18]. In addition HVOF have reduces downtime, quick to apply, low environmental impact compared to electroplating processes, and improved density and less cracks and pores [19].

The main disadvantages of HVOF spraying include: It can be more complex, with their properties and microstructure depending upon several processing variables, powder sizes is restricted to a range of about 5 - 60 μ m, with a need for narrow size distributions. In addition it is costly and requires qualified personnel to ensure safe operation, and to achieve consistent coating quality. Deposition of coatings is difficult or impossible to achieve on to internal surfaces of small cylindrical components, or other restricted access surfaces, because HVOF spraying needs line of sight to the surface and a spray distance of 150-300 mm.

B) Applications:

The HVOF sprayed coatings have found wide application in marine, oil and gas, paper, petrochemicals, aircraft, automotive, power, mining, chemical, and other industries. For reclaiming a wide range of petrochemical-process components such as storage vessels, heat exchangers, pipe end fittings and valves, which are subjected to severe erosive, wear and corrosive conditions, Amoco Oil Company routinely employs the HVOF process by applying AISI 316 L and Hastalloy C-276 coatings [20]. The HVOF thermal spraying process has also been successfully employed to repair stainless steel and D2 tool steel substrate with different depth of damage to a built-up thickness of up to 5.5 mm. Sprayed material had good adherence to the substrate under various types of aggressive machining processes [21]. It is a relatively cool process which leads to minimal distortion or

metallurgical change to the sprayed material. In addition the HVOF Coating most commonly used as a replacement for environmentally damaging Hard Chrome, Pumps, Seals, Valves, wire drawing equipment, hard chrome replacement, Actuators, Impellers, Rams, Pistons, Bearings, Shafts, Wear and corrosion protection, Wear Rings, valve plugs and Drilling Tools. HVOF is extensively applicable for high-quality production, wear-resistant coating of satellites and carbides [22].

c) Comparison of Thermal Spray Process.

Table 1. Comparison of characteristics for various thermal spraying processes [23]

S.No	Process	Heat source	Propellant	Material feed type	Spray gun temp. (°C)	Particle velocity (m/s)	Coating materials	Porosity level vol. %
1	Electric arc	Arc between electrodes	Air	Wire	6000	240	Ductile materials	8-15
2	Plasma arc spraying	Plasma arc	Air	Wire	6000	120-600	ceramic, plastic, and compounds	2-5
3	Low pressure plasma spraying	Plasma arc	Inert gas	Powder	16000	500	Metallic, ceramic, plastic, and compound	< 5
4	Flame spraying	Oxy-acetylene/ oxy-hydro gen	Air	Powder	3000	30-120	Metallic and ceramics	10-20
5	D-Gun	Oxygen acetylene	Detonation shock waves	Powder	4500	800	Metallic, ceramic, plastic, and compounds	0.1-1
6	HVOF	Oxypropylene/ hydrogen/ propane/ LPG	Combustion jet	Powder/ wire	3000	800	Metallic and ceramic	0.1 – 2

2. LITERATURE REVIEW

In this section studies by various researchers in simulated and actual boiler environment are presented.

T.S. Sidhu et al. [24] successfully deposited NiCrBSi coating on SN 600, SN 601, and SF 800H steel in simulated boiler environment at 900°C using HVOF process. The author found that NiCrBSi coating on SF 800H reduce maximum hot corrosion 80%, while NiCrBSi coating on SN 600 and SN 601 steel reduce hot corrosion by 40% and 65% respectively. H.S. Sidhu et al. [25] studied the hot corrosion behaviour of Cr₃C₂ NiCr, NiCr, WCCo, and Stellite -6 coating on T11 boiler tube steel at 900° under simulated environment. From the experimental results it was observed that the aforementioned coating reduced hot corrosion 89%, 94%, 40 and 53% respectively. The bare steel GrA1 shows poor result of hot corrosion as compared to coated steel. T.S. Sidhu et al. [26] investigated hot corrosion performance of NiCrBSi, and Stellite-6 coating on SN 600 substrate at extreme temperature in boiler environment. The NiCrBSi, and Stellite-6 coating were found to be less useful as it reduce hot corrosion by 37% and 21% respectively. Many authors [27-30] deposited HVOF sprayed, WC-

Co, satellite-6, Ni, Cr, and Fe, based coating on boiler steels (347H, T91, T22, SN 601, SN 75 and SN 718) at 900°C. From the result it is observed that Cr3C2-25(Ni20Cr) coating on T91 decrease maximum hot corrosion (80%). H.S. Sidhu et al. [31] successfully deposited NiCr coatings on GrA1, T-11, and T-22 boiler steels by LPG (liquefied petroleum gas) assisted HVOF spray process. The kinetics of corrosion was studied using thermogravimetric at 900°C in the molten salt atmosphere. From the experiments result of SEM/EDAX, XRD and EPMA techniques, the NiCr coating on GrA1, T-11, and T-22 steel reduce hot corrosion in the order of 96.97, 94.13, and 95.26% respectively. This may be due to the formation of protective oxide such as NiO, Cr₂O₃ and NiCr₂O₄. The porosity, thickness, and average microhardness of the NiCr coating were found to be less than 1%, 300 µm, and 400Hv respectively. The bare steels specimen shows Fe₂O₃ as the main ingredient of scale. Whereas coated samples indicate the presence of Fe₂O₃, Cr₂O₃, NiO and NiCr₂O₄ phases in the scales. The uncoated boiler tube steels samples showed peeling of scale, intense spalling, cracking and enormous weight gain during hot corrosion studies in Na₂SO₄-60%V₂O₅ at 900°C. Whereas coated selected specimen showed more hot corrosion resistance. T S Sidhu, S Parkash and R D Aggerwal et al [32] investigated the hot corrosion behavior of a Ni-based super alloy (19.5Cr-3Fe-0.3Ti-0.1C-balance Ni) coated by Cr3C2-NiCr, NiCrBSi, Stellite-6 and Ni-20Cr powders using an HVOF process. From the investigation it was found that Ni-20Cr shows better result of hot corrosion as compared with satellite-6 coating. M Kaur, H Singh, and S. Prakash et al. [33] successfully deposited Cr₃C₂-NiCr coating on SAE-347H boiler steel by High velocity oxy fuel process. The base steel SAE-347H shows poor result of hot corrosion (6.17 mg/cm²) as compared to coated steel (2.925mg/cm²). Rakesh Bhatia, H. S. Sidhu, B. S. Sidhu et al. [34] Studied the usefulness T91 boiler tube steel coated by 75% Cr3C2 -25% (Ni-20Cr) coating powders by HVOF technique to control hot corrosion at various temperatures i.e. 550,700. The bare steel T91 indicates poor result of hot corrosion as compared to coated steel at all operating temperatures. Singh et. al. studied that to prevent from corrosion T91 boiler tube steel, the coatings of powder Cr3C2-25 (Ni-20Cr) and Ni-20Cr were deposited by high velocity oxy-fuel (HVOF) process. The bare and coated T-91 steel samples were tested for hot corrosion studies in molten salt (Na₂SO₄-60%V₂O₅) environment at 900°C temperature under cyclic conditions and each cycle consisted 1 h of heating in tube furnace followed by 20 min in air cooling. Using thermo gravimetric technique, the weight change measurements were tested after each cycle in order to establish the kinetics of corrosion. To analyze the corrosion products, x-ray diffraction and scanning electron microscopy/energy dispersive x-ray analysis were used. The uncoated steel has higher weight gain during testing due to the formation of un-protective Fe₂O₃ dominated oxide scales. The Cr3C2-25(Ni-20Cr) coating was found more protective and have better results than the Ni-20Cr coating [35]. Chatha et. al. investigate that 75Cr3C2 -25NiCr coating can be deposited by high velocity oxy-fuel (HVOF) process on T91 boiler tube steel substrate to enhance high-temperature/hot corrosion resistance. In the present investigation high-temperature corrosion behavior of bare as well as coated steels were evaluated. For this investigation, the experiments were conducted at 900°C for 15 cycles each of 100 h duration and 1 h cooling at ambient temp. The investigation of the bare and coated steel specimens were done with the help of metal thickness loss and corresponding to the corrosion scale formation and also with the depth of internal corrosion attacks. The bare boiler tube steel suffered from a catastrophic degradation in the form of internal oxidation attack and thickness loss. The 75Cr C -25NiCr coating shows good result as compare to bare steel and also no tendency for internal oxidation [36]. From the literature it has been concluded that although the work has been done in the field of erosion and corrosion testing of thermal spray coated steels, but more research is needed to evaluate the performance of these coatings in more aggressive environments, whether in the laboratory conditions or in actual boiler conditions. More work is needed to understand the combined effect of erosion- corrosion (E-C) of HVOF sprayed of different coatings on different materials.

3. CONCLUSION

It has been concluded from the results of various researchers that HVOF process have gaining high potential due to increased thickness capability (200-300 µm), higher micro hardness, less porosity usually < 1%, dense coating and good adhesion strength. Further, it has been concluded that Ni-Cr based coatings offered very high hot corrosion resistance. In addition HVOF process is widely used for commercial applications, since

it provides well bonded, wear resistant and corrosion resistant coatings, Moreover, the application of HVOF coating to the operating components will increase working life of these components.

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