

MECHANICAL DEGRADATION OF VARIOUS WEAR RESISTANT NANOSTRUCTURED COATING SYSTEMS

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ABSTRACT

Material degradation due to wear is recognized as a severe problem in coal based power plant, hydro power plant, gas turbine, aircraft, petrochemical industries, automobile industries and in various industrial components. Wear is greatly responsible for huge amount of losses in the performance, efficiency and cost. Wear is a surface phenomenon and optimize solution to protect the material from the degradation is required so that it can protect the surface of bare substrate. In order to reduce the effect of wear and erosion and for lengthen the service life of the component thermal spray processes are the most effectively solutions for inhibiting the erosion. Thermal spray processes are established industrial method for deposit coatings for resurfacing the metal parts. Thermal spray processes are gaining popularity due to its high hardness, dense structure, wear resistant and cost effective. The process is carried out by melting and transporting of sprayed material usually metal or ceramics on the part surface/substrate. Carbide based nanostructured coatings using various thermal spray processes are suitable method for lengthen the service life of the component by improving the erosion wear resistance. High velocity oxy fuel, detonation gun spray and plasma spray are some most effectively use thermal spray process due to their high hardness, dense, high wear resistance. In this paper analysis of previous literatures and comparative study on thermal sprayed wear resistance nano-structured coatings are reviewed.

Keywords- *Erosion, Wear resistance coatings, Thermal spray process, HVOF, D-Gun spray, Plasma spray.*

I. INTRODUCTION

Degradation of material due to erosive wear is a severe problem in many industries due to presence of erodent in the environment [1]. Marine, aeronautical, hydro power plants and automobiles are very common examples where huge amount of losses occurs due to erosion and hence reduces the life of components, their functioning and the efficiency of the plant. In the industries the components like regulating valves, pipelines, extrusion dies, powder mixtures, pumps, turbines, blades of wind turbine, and helicopter blades are operated in the erosive environment [2]. The erosive particles which are suspended in the environmental air or in the water can strike at

the external or internal surface of the components and responsible for excessive removal of material from the surface, this is termed as erosion.

The erosion mechanism is function of a number of parameters like impact angle, material properties, speed, concentration of particles, size and shape of erodent and the temperature [3]. In case of a ductile material the material removal occurs in some specific ways such as ploughing and cutting but in case of brittle materials this mechanism is fragmentation and removal of flakes [1]. Materials having brittle phase experienced the severe erosive wear at normal angle condition and shows the good wear resistance for the low around 20° to 45° angles and the ductile material suffered by maximum wear at almost 20° impact angle and has good wear resistance for 90° impact angles [4, 5]. Due to the erosion the almost estimated cost up to US\$150 million in a year is wasted in maintaining efficiency, forced outage and the repair cost in the power plant industries [6].

The continuous advancement in industries requires a material which is capable to withstand against the high temperature, pressure and the industrial environment which contains several erosive species [7]. It is impossible for a single material to have all the desired mechanical properties to meet the industry's demands therefore a composite system of base material with a protecting surface layer different in structure or/and in chemical composition with desired mechanical properties and higher erosive resistance can be the optimum choice of the industry's demands in that environment [8]. The coatings behave like a barrier between the material and the environment and protect the material without disturbing the desired mechanical properties of base material. Various compositions of tungsten carbide and chrome carbide based nanostructured as well as conventional coatings are used to reduce the erosive wear. The WC based coatings shows the greater erosion resistance and limited up to the 450°C temperature whereas chrome carbide based coatings are widely used for protection against the erosion at elevated temperature up to 900°C [9,10].

II. EROSION

Erosion is the phenomenon of degradation of material from the surface due to mechanical interaction between the component and the erodent. It is recognized as a very severe problem in many industries like aerospace, jet engines, hydro power plants, automobiles, slurry transportation system and mining where erosion limits the use of the component and considerable reduce their reliability and durability [12]. Erosion and high temperature corrosion is severe problem to be solved in industries and especially in those area where temperature range is above 600°C, it increase the corrosion probability due to removal of protective surface layer from the surface of the material by the erosive action [13]. Erosion takes place due to cutting and deformation mechanisms. When the erodent flow parallel to the surface then the material is removes due to cutting wear and if erodent impinge normal to the surface then it is due to deformation wear [1]. The mechanism of erosive wear involves both brittle fracture and the plastic deformation and this is depending on the impact conditions [14]. The erosive mechanism is the function of many parameters that is the properties of erodent (size, shape and hardness), concentration of particles, impact angle, speed and properties of base material i.e. brittle or ductile, hardness, wear resistance and the environmental conditions that is temperature and pressure, media etc. [3]. The erosion strongly depends on the kinetic energy of particles, number and mass of individual particles striking the surface and the impact angle [2].

Prakash et al. [33] reported that the erosive wear is responsible for a large number of failures in boilers, about 56.18% failures in plant are results of erosion due to ash and hot corrosion. The failure type with their occurrence percentage is shown in table 1. Some examples of failures in fluidized boiler tubes erosive wear is shown in fig 1[34].

III. AFFECTING PARAMETER OF WEAR AND PROTECTIVE SYSTEM

There are many factors that greatly affecting the wear mechanism. It broadly consists of the properties of base material, properties of erodent and the nature of environmental conditions [3]. The abrasive and erosive wear can be significantly minimized by controlling its affecting parameters. Patil et al. [15] studied the various affecting parameters of wear mechanism for aluminum using sand particles as erodent. In this investigation the velocity of sand particles is constant at 3.68m/sec and the particles size 225 μ m, 505 μ m and 855 μ m are use and observed that the erosive wear is maximum for larger particle size (i.e. 855 μ m) which is 161.6mm/year and the rate of wear increases linearly with the particle size. Due to ductile nature of aluminum the maximum wear is recognized at 45° angle and after further increase in angle it decrease for all three particles. Hutchings et al [14] shows the effect of particle's shape on wear mechanism and gives a relation regarding the shape of the particle. The relation is

$$F = \frac{4\pi A}{P^2} \quad (1)$$

Where the roundness factor or shape factor F is defined as the ratio between the projection area and the area of a circle with the same perimeter P as the projection. Lesser value of shape factor indicates the greater angularity of erodent. Wear is increase with increase in angularity therefore the wear is increase as the value of shape factor decrease. The effect of the of the shape factor on the erosive wear performance is shown in table 2.

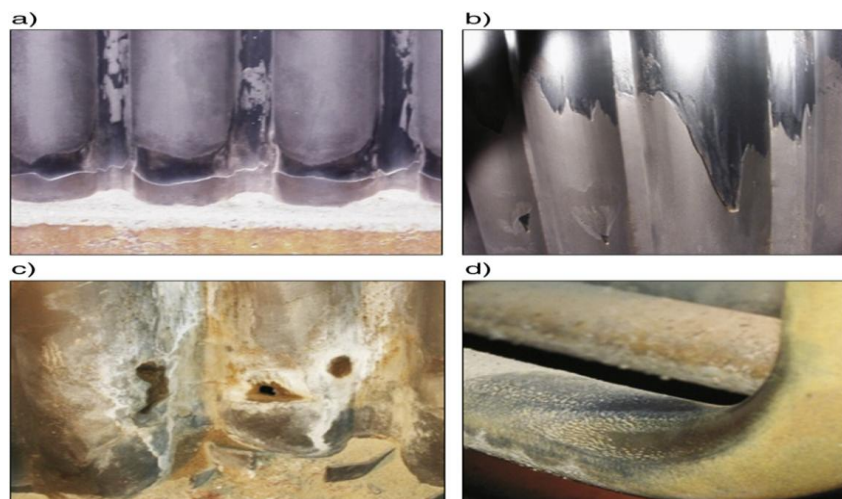


Figure 1: Typical examples of erosive wear in fluidized boiler: a) the area over the ceramic lining, b) transition zone in thermally sprayed coatings, c) damage caused by erosion of the wall, and d) damaged superheater tube [34].

Table 1: Boiler tube failure analysis [33].

S.No.	Type of Failure	No. of failure out of 89	Percentage(%)
1.	Erosion due to ash and hot corrosion including overheating due to corrosion	50	56.18
2.	Erosion due to pulverized fuel from coal nozzles	12	13.48
3.	Welding joints cracks	10	11.24
4.	Overheating due to choking	8	8.99
5.	Leakage from water walls, header drains due to expansion and contraction	5	5.62
6.	Miscellaneous	4	4.49

Table 2: Effect of shape factor on wear performance

Sr. No.	Erodent	Shape	Modified Shape factor	Wear Performance	Ref.
1.	Silicon carbide	Angular	0.4425	High	1
2.	Alumina	Angular	0.3425	Highest	
3.	Quartz	Blocky	0.7007	Lower	

IV. WEAR RESISTANT COATINGS

Coatings are the suitable solution for improving the erosion and wear resistance of the base material with the desired mechanical properties. Tungsten carbide and chrome carbide based coatings are widely used as the wear resistant coatings for high temperature applications and as the alternative of hard chrome plating [11]. Murthy et al [11] study the comparative wear behaviour of tungsten carbide based, chrome carbide based coatings deposited by Detonation gun and High Velocity Oxy Fuel method, hard chrome plating and the bare substrate with dry silica sand particles as erodent. It is observed that the WC-10Co-4Cr coating shows greater abrasive

wear resistance as compared to $\text{Cr}_3\text{C}_2\text{-20NiCr}$ due to high hardness of WC and better matrix properties due to CoCr binder and the D-gun sprayed coating has greater wear resistance as compared to HVOF sprayed due to its high density, bond strength. Cermet of Co matrix resists wear better than the Ni matrix and addition Cr improves the erosion resistance. The comparative wear behaviour of WC-10Co-4Cr, $\text{Cr}_3\text{C}_2\text{-20NiCr}$, hard chrome plating and bare substrate is shown in fig 2. The hardness of the thermal sprayed coating is greatly influenced by the characteristics of the feed stock powder [16,18]. It has been investigated that the nanostructured material often demonstrates higher hardness as compared to the conventional material [19]. Cunha et al [20] use a conventional feed stock powder $\text{Cr}_3\text{C}_2\text{-25(Ni20Cr)}$ of average particle size $25\mu\text{m}$ and for nanostructured milling is done on it and reduced the average particle size to $11\mu\text{m}$. The coating of conventional and nanostructured $\text{Cr}_3\text{C}_2\text{-25(Ni20Cr)}$ is deposited on AISI 310 steel using HVOF method. The hardness and the fracture toughness of the nanostructured $\text{Cr}_3\text{C}_2\text{-25(Ni20Cr)}$ is higher than the received powder due to its uniform microstructure and inherently high hardness of nanostructured material. Wang et al [24] studied the comparative behaviour of nanostructured as well as conventional coatings of powder composition $\text{Al}_2\text{O}_3/\text{TiO}_2$ and with some additives that is CeO_2 and ZrO_2 deposited by plasma spray technique. He was observed after carryout the experiment that the wear resistance is greatly improved for nanostructured $\text{Al}_2\text{O}_3/\text{TiO}_2$ powder as compared to the conventional powder. The additives $\text{CeO}_2+\text{ZrO}_2$ in the coating powder increase the wear resistance three times of the nanostructured coating whereas the hardness of coating is almost same.

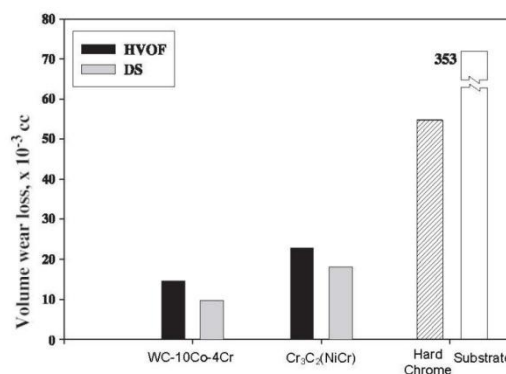


Figure 2: Bar chart cumulative wear loss of thermal spray coatings with hard chrome and bare substrate [11].

V. THERMAL SPRAY PROCESS FOR DEPOSITION OF WEAR RESISTANT COATINGS

Various methods and techniques are used for protect the material from the degradation. In order to enhance the wear resistance and extend the life of components thermal spray methods are viable solutions with improving the surface properties of material. It is an effective and low cost method for deposit coatings of wide range of thickness [27]. In various thermal spray process we use the combustion of fuel such as kerosene, LPG, oxy acetylene gas or the plasma energy to melt and accelerate the particle which strikes on to the surface of the base material and a uniform crack free solid layer is formed over the surface [28]. Thermal spray processes are classified on basis of the heat source used to melt the feed stock particles/powder for deposition/coating. By use

of suitable coating composition and appropriate thermal spray method, the desired properties of coating can be achieved. There are many thermal spray techniques are available like high velocity oxy fuel (HVOF) method, detonation gun (D-gun), plasma spray and flame spray etc. The selection of the suitable thermal spray process is based on the coating material, coating performance requirement, properties of base material, economics and the size and shape of the part. The various properties of thermal spray process deposited by different methods in shown in table 3.

5.1 High Velocity Oxy Fuel Method

The high velocity oxy fuel (HVOF) method is mostly used thermal spray process for deposit coating of various composition and various thickness due better properties like hardness, very less porosity, high bond strength, uniform and dense structure and their cost effectiveness. In HVOF process the fuel (hydrocarbon) is burn in oxygen and generate a flame of supersonic velocity and then the feed stock powder is introduced axial direction which melts and accelerates and achieve a velocity up to 550m/sec. and it provide a wide range of thickness of coating between .05mm to .50mm [29]. The various properties of the HVOF sprayed coatings are shown in table 3.

5.2 Detonation Gun Spray Method

Detonation gun (D-gun) spray method is a thermal spray process which gives high adhesive strength, very low porosity and good bond strength because the very high (almost 3500m/sec.) velocity of melted particles [30]. In this method a predetermined amount of particle in injected in the combustion chamber of gun barrel where the mixture of oxygen and acetylene gas ignites by a spark plug. The combustion of gas mixture produce a high pressure shock wave i.e. detonation wave. The shock waves attain a velocity up to 3000m/sec and accelerate the particles to a velocity of 800m/sec [29]. The properties of D-gun spray coatings are shown in table 3. The schematic diagram of D-gun process is shown in fig 3.

Table 3: Properties of different coating deposited by different thermal spray techniques

Sr. No.	Coating composition	Deposit on method	Hardness	Thickne ss μm	Remarks	Porosity (%)	Ref.
1.	WC-10Co-Cr	D-Gun	1007±35H V _{0.3}	300±50	Higher density and compressive residual stress induced in coating.	1.38±0.3	11
2.	Ti-N-Cr	Vacuum arc	3222±112. 2HV	2.9±1	Uniform nitrogen distribution in coating & formation (Ti, Cr) ₂ N, Cr ₂ Ti compounds, that results in small grain dispersion.	—	22

3.	WC-Co	HVOF	1350HV _{0.5}	—	Coating consists hard WC grains with ductile Co binder.	<1	17
4.	WC-10Co-Cr	HVOF	836±30HV _{0.3}	300±50	Partial decarburization of WC to W ₂ C, selective removal of binders due to plastic deformation and fatigue.	2.1±.1	11
5.	WC-CoCr	HVOF	940HV	170	Due to hard grain of WC, coating successfully reduce the erosive wear.	—	2
6.	WC-12.5Co-1.5Cr	HVOF	963±99HV _{0.3}	200-350	Phase transformation in W ₂ C or (W,Cr) ₂ C during spray process, and results in very lower porosity.	1.4-2.2	21
7.	Cr ₃ C ₂ -20NiCr	D-Gun	810±25HV _{0.3}	300±50	Delaminating type material removal & matrix phase has not an efficient toughening phase.	0.65±0.3	11
8.	WC-4Cr ₃ C ₂ -12Ni	HVOF	1012±90HV	200-350	Induce higher density due to formation of metallic tungsten during spray.	0.7-1.8	21
9.	WC-10Co-4Cr	D-Gun	1114±100HV	250	Removal of carbon (decarburization) from WC-Co powder during processing.	—	23
10.	WC-14CoCr	HVOF	1269 HV	300	Cermet of Co matrix resist better than Ni matrix & Cr improves the erosive resistance of WC-Co by a factor of 4 to 6.	—	25

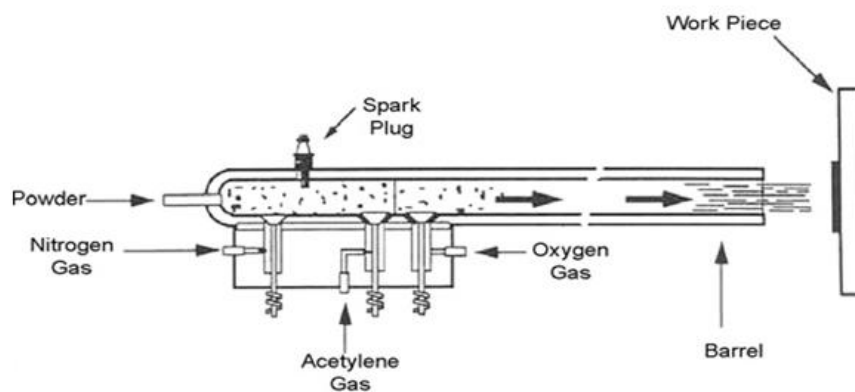


Figure 3: schematic diagram of detonation gun spray process [31].

5.3 PLASMA SPRAY PROCESS

Plasma spray is a type of thermal spray process. Plasma spraying is achieved by the plasma torch. In this method a high intensity arc is operated between the stick type cathode and nozzle shaped anode which is water cooled. The plasma gas is inserted along the cathode which is heated up to the plasma temperature by the arc and leaving the nozzle as a plasma jet. The fine particles suspended in carrier gas are injected into the plasma jet and then heated and accelerate. Then the molten particle impinges on the surface and form a less or more dense coating depends on the operating parameters [32]. The properties of plasma sprayed coatings is shown in table 3.

VI. CONCLUSIONS

The following conclusions are made

- ✓ Erosion is the function of various parameters i.e. impact angle, particle size and shape, speed and concentration etc.
- ✓ The material removal mechanism in ductile materials is ploughing and cutting but in brittle material it is fragmentation and removal of flakes.
- ✓ Brittle materials possess higher wear resistance at around 20° to 45° impact angle but ductile material having maximum wear at 90° impact angle.
- ✓ The tungsten carbide based coatings shows the greater wear resistance than the chrome carbide based coatings.
- ✓ Nanostructured coatings exhibits the greater wear resistant properties as compared to conventional coatings due to its high hardness and high grain boundary area
- ✓ The nanostructured powder material for coating shows the higher erosive wear resistance as compared to the conventional powder.
- ✓ All thermal spray process have greater wear resistance as compared to hard chrome plating.

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