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Erosion and Hot Corrosion Phenomena in Thermal Power Plant and their Preventive Methods: A Study

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***Abstract* - Erosion and hot corrosion in coal fired boiler at elevated temperature is the primary reason behind downtime in power generating plants. In the present study an attempt has been made to study the basic concept of erosion, types, mechanism and tribological parameters that affect erosion wear. In addition, types and stages of hot corrosion have been discussed in brief with an emphasis on different protective methods for erosion such as use of super alloy, inhibitor, protective coating and hard facing. The distinct investigations have been carried to overcome the erosion and hot corrosion problems and found that erosion resistant coating and hard facing are effective way to resist degradations of erosion-corrosion (E-C) in a coal fired boiler.**

***Keywords:* Hot Corrosion, Erosion, Hardfacing, Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), Thermal Spraying**

I. INTRODUCTION

As per the latest statistics mentioned in ‘Annual Report 2016-17, Ministry of Power, Govt. of India’, the total installed power generation capacity in India was 3,29,205 MW, out of which 59% (194,231 MW) was shared by coal based thermal power stations. This share of coal-based installed capacity has been continuously increasing since 1977 (www.powermin.nic.in). Since the trend of coal-based generation has been increasing continuously, therefore the loss involved due to material degradation at high temperatures has further rising in coal fired boilers. Hence there is a need to address high temperature corrosion and erosion problems of power plant boilers.

Erosion corrosion (E-C) is a synergistic process comprising both erosion and corrosion (E-C), in which each of these processes is influenced by the simultaneous action of the other, and in many cases as a result of that it accelerated. In present days, most of engineering parts often fracture/damage when its surface can’t withstand the external forces to which it is subjected. Therefore, it is essential to select such different types of material having good thermal, optical, magnetic, mechanical, chemical and electrical properties and maximum resistance to wear, corrosion and degradation. Therefore, for maximum utilization of high performance machinery components, an understanding the basic concept of erosion corrosion (E-C) and to promote effective preventive system is necessary.

II. EROSION

Erosion is the process of wear in which material are removed directly from the upper surface by the impingement of the small size solid particle at high speed on it. Erosion is mostly commonly occurring in boiler, turbine blade, etc that decreases the life of equipment. Erosion is most widely used in abrasive jet machining, sand blasting, and erosive drilling of hard component. In case of coal fired boiler, fly ash particles, strikes on the boiler tubes & wear down. Erosion in a steam generator tube takes place initially when the coal fell down along the surface of tubes and coal attack on surface of tubes (due to the air feeding).

A. Types of Erosion Wear

On the basis of interaction between the material surface and the impacting substance, erosion wear can be divided into four different types’ namely solid particle erosion, slurry erosion, cavitation erosion, and liquid impingement erosion.

1. Solid Particle Erosion (SPE): It is the type of erosion process in which loss of material takes place caused by repeated impact of small, solid particles entrained in air/gas at any significant velocity. SPE is a major problem for the electric power industry, and jet turbine, pipe line, and steam turbine etc. It costs an estimated US$150 million a year in lost efficiency, forced outages, and repair costs [1]. Erosive, high temperature wear of heat exchanger tubes and other structural materials in coal-fired boilers are recognized as being the main cause of downtime at power-generating plants, which could account for 50-75% of their total arrest time. Maintenance costs for replacing broken tubes in the same installations are also very high, and can be estimated at up to 54% of the total production costs. High temperature oxidation and erosion by the impact of fly ashes and unburned carbon particles are the main problems to be solved in these applications. Hence, the development of wear and high temperature oxidation protection systems in thermal power plant is a very vital issue from both engineering and an economic view point [2].

In 1981, Bellman and Levy [3] suggested a mechanism of macroscopic erosion that particles hitting the material surface make shallow craters and platelet-like pieces. These platelets are uncomplicated to separate from the material surface by successive particle impact as shown in Fig. 1. It is found that adiabatic shear heating on the material surface and work-hardening under the surface occur during the development of platelets.

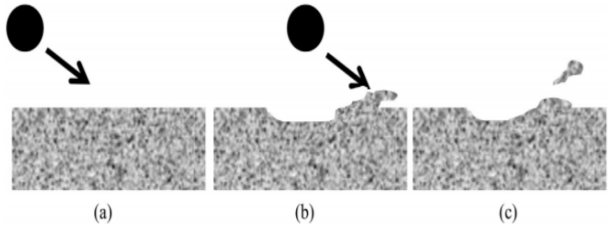

Fig.1 Schematic of Erosion Procedure in Ductile Material (a) before the impact, (b) crater formation and piling material at one side of the crater, (c) separation of material from the surface. [4]

Different researchers suggested other SPE mechanism for ductile materials [5-8]. On the other hands in case of brittle material the SPE mechanism is caused by crack formation [9-11]. When a solid particle impinges on a brittle surface, it generates radial as well as lateral cracks. These generated cracks split the material surface into smaller parts as shown in Fig.2.

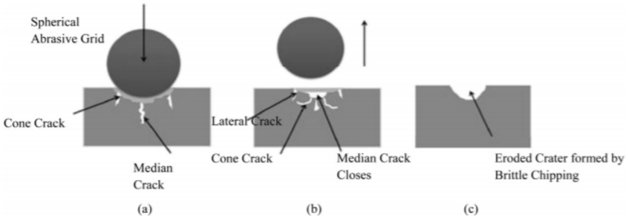

Fig. 2 Expected Mechanism of Erosion in Brittle Material: (a) growth of cone crack and median cracks (b) closure of median and creation of lateral cracks, (c) eroded crater formed [12]

2. Cavitations Erosion (CE): It is the type of erosion in which repeated nucleation growth and violent collapse of bubbles in a liquid takes place.In practice, all liquids contain gaseous, liquid and solid impurities which act as nucleation sites for the cavities. When the liquid that contains cavities is consequently subjected to compressive stresses, that is, is more hydrostatic pressure, these cavities will collapse. This collapse is directly responsible for this process. CE has long been identified as one of the serious problems in the design and operation of modern high-speed flow systems, such as turbo machinery, high speed mixing system, flow control valves, high-frequency ultrasonic devices, fast nuclear reactors, etc.

In Dular, M., *et al.,* 2006 [13] suggested the mechanism of cavitations erosion. When the bubbles collapse, the potential energy (P.E) present in bubbles converts into acoustic energy and radiates strong acoustic pulsations in the fluid. The magnitude of this shock wave was attenuated with traveling distance and arrive the bubble existing near the clouds. Subsequently as soon as the pressure wave reaches another bubble, it oscillates and deforms together. Simultaneously, the bubble moves with certain velocity and hits the material surface. Hence, the bubble imploded very near to the surface. The micro jet developed during implosion influences the surface. Due to this an impact pressure was created at the interface between the microjet and material surface. At the same time, the shock wave was also radiated near the surface. When the value of impact pressure increase beyonds the yield strength of material, permanent deformation occurs at the surface. Fig. 3 shows the mechanism of oil cavitation jet erosion in a ductile material.

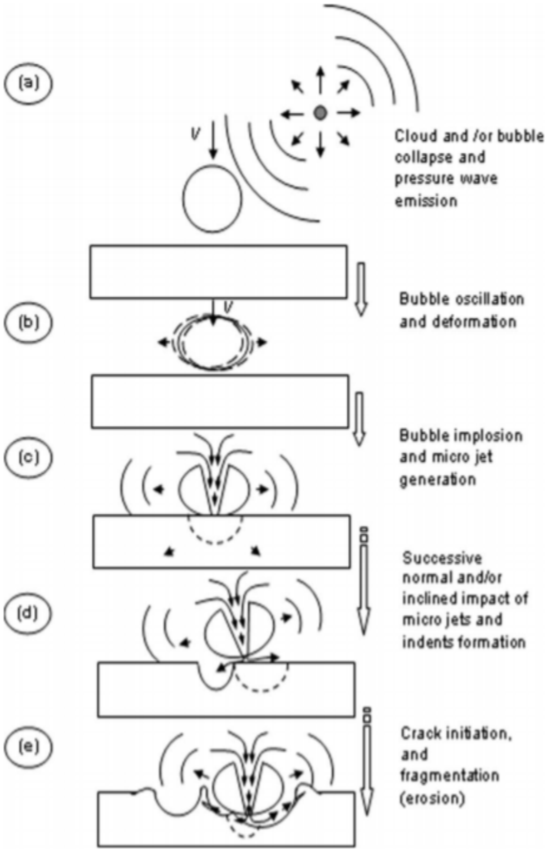

Fig.3 Mechanism of Oil Jet Cavitation Erosion on Ductile Materials: (a) collapse of clouds and/or bubbles, and pressure wave emission (b) Bubble oscillates and deforms near the surface (c) Implosion of bubble and micro jet formation (d) Subsequent implosion of another bubble of oil cavitation jet forms craters and (e) initiated the cracks in the rims, crack growth, and fragmentation of rims due to radial force.

3. Liquid Impingement Erosion (LIE): It is the progressive loss of original material from a solid surface due to continued exposure to impacts by liquid drops or jets. Liquid impingement erosion is similar to repeated impacts or collisions between the surface being eroded and small discrete liquid bodies. The significance of the discrete impacts is that they generate impulsive contact pressures on the solid target, far higher than those produced by steady flows thus, the fatigue limit and even the yield strength of the target material can easily be rise above, thereby causing deterioration by completely mechanical interaction. It occurs in elbows, T junctions and the pipe walls downstream of the orifice in the pipelines, where the flow velocity through the pipeline is highly increased causes pipe wall thinning in power plants [14]. LIE mainly depends upon flow velocity. Fig.4 shows the liquid impingement and impingement erosion.

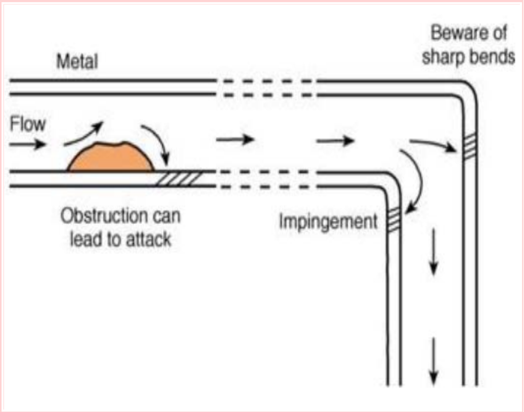

Fig.4 Liquid Impingement and Impingement Erosion [14]

4. Slurry Erosion (SE): It is the type of wear that occurs when a material is exposed to a jet of slurry (mixture of solid particles in a liquid). It takes place when the material passes through the slurry or when the slurry moves past the material at a certain velocity. Slurry erosion is a serious problem for the industries, which deals with the liquids having solid particles entrained in them such as in hydro turbines and other fluid machineries wherein erodent particles entrained in carrier fluid impinge upon the target surface to cause its degradation. Several possible alternative solutions are available to control slurry erosion; however, surface coatings developed using thermal spraying are mostly used owing to their versatile nature The presence of sand particles in the river water fed to hydro turbines results in their severe wear.

The impingement of the sand particles entrained in water on to the solid surface results in the removal of materials, known as slurry erosion. Erosion of hydropower plants may results in substantial loss of revenues. According to an estimate given by Mann and Arya [15], in 1998, India incurred a loss of US $ 120 – 150 million due to slurry erosion. Another government report says that shutting down of Naptha Jhakri power plant during the periods of high silt load, resulted in a loss of US $ 77 million during the year 2003 to 2005 [16]. To reduce the damaging effects of slurry erosion, numerous surface modification techniques are utilized. These methods provide low cost solution to deal with such degradation. Among these techniques, thermal spraying has attracted considerable attention worldwide owing to its versatile nature [17] Schematic diagram of slurry pot and slurry jet is shown in Fig.5.

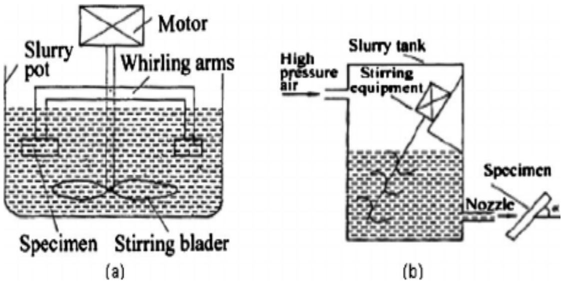

Fig.5 (a) Schematic Diagram of a Slurry Pot, and (B) Schematic Diagram of a Slurry Jet Tester [18]

B. Parameters Affecting Erosion Wear

The parameters which affects the erosion wear is shown in Fig.6.

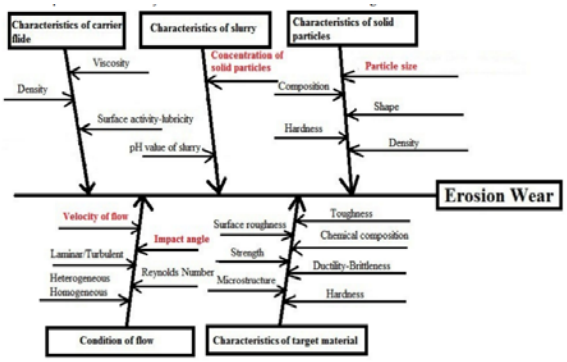

Fig. 6 Factors Affecting Erosion Wear (cause & effect diagram) [19]

The above cause and effect diagram is mainly concerned with five different parameters namely: characteristics of carrier fluid, solid particles, slurry, target materials and flow condition. The particle size, shape, hardness, composition, and density are the sub parameters affecting erosion wear. From all the parameters the four parameters namely impact angle, particle size, velocity of flow and concentration of solid particles are the most effective parameters that handle the erosion wear. [19]

III. HOT CORROSION OR DRY CORROSION OXIDATION.

It is a type of corrosion comprising the reaction between a metallic elements and air or oxygen at elevated temperature in the absence of water. The rate of hot corrosion/ oxidation of a metallic element at elevated temperature mainly depend on the nature of the oxide layer that develops on the metallic surface [20]. It increases when the surface of metallic elements are coated with a thin film of fused salt in an oxidizing gas environment. Such type of corrosion attack is known as hot corrosion. It was first identified as a major problem in the 1940s in connection with the degradation of fireside boiler tubes in coal-fired thermal power plant. Since the problems has been observed in boilers, internal combustion engines, gas turbines, fluidized bed combustion and industrial waste incinerators [21]. In other words hot corrosion may be defined as accelerated corrosion, resulting from the presence of salt contaminants (NaCl, Na_2SO_4, and V_2O_5) that combine to form molten deposits, which damage the protective surface oxides [22].

A. Types of Hot Corrosion

1. Type I Hot Corrosion: It occurs at elevated temperature 850-950°C (above melting point of Na_2SO_4) [23-24].It begins with the condensation of fused alkali metal salts like sodium sulfide, sodium carbonate, and sodium acetate etc., on the surface of the exposed parts to elevated temperature. Then the chemical reaction occurs and initially attacks the protective oxide film and continuously reduces the chromium (Cr) content of the substrate materials. Due to the reduction in chromium content, oxidation of the substrate rapidly increases and porous scale form.

2. Type II Hot Corrosion: It takes place at 650–800°C temperature (less than the melting point of Na_2SO_4, in the presence of small amount of SO_3) [25-26]. It is described by a pitting attack with little attack underneath. In this type of hot corrosion, low melting point eutectic mixtures of Na_2SO_4 and $CoSO_4$ cause typical pitting in the confined areas. In low temperature hot corrosion microscopic sulphidation & chromium depletion is normally not noticed [27]. This type of corrosion is mainly occurs in industrial marine and gas turbines.

IV. MECHANISM OF HOT CORROSION

The hot corrosion of super alloys takes place in three different stages [28]

1. First stage (incubation stage): the reaction proceeds at a rate similar to normal oxidation.
2. Second stage (initiation stage): the corrosion is accelerated.
3. Third stage (propagation stage): rapid corrosion takes place. After this stage ultimate failure of a component take place.

V. PREVENTIVE MEASURES

Thermal sprayed coatings are economical, can be produced by means of easy techniques and give excellent erosion and corrosion protection. As a result these coatings have found use in various industrial applications. High temperature oxidation and erosion by the impact of fly ash and unburned carbon particles are the main problems to be solved in heat exchanger tubes and other structural materials in coal-fired boilers. Therefore, the development of wear and high temperature oxidation protection systems in industrial boilers is a very important topic from both engineering and an economic point of view. The use of different coals under a variety of combustion conditions, ranging from widely varying combustion gas chemistry to widely varying nucleation, growth and condensation of particulates, can have a direct effect on material degradation in these systems. Regarding use of inhibitor, addition of an organic inhibitor (e.g. pyridines, pyrimidines, quinolines) is sufficient to mitigate corrosion of metals in many corrosive media.

An inhibitor is a chemical substance or combination of substances that, when present in the environment, prevents or reduces corrosion without significant reaction with the components of the environment. The application of inhibitors must be viewed with caution by the user because inhibitors may afford excellent protection for one metal in a specific system but can aggravate corrosion for some other metal in same system. However, these inhibitors have shown only limited success due to solubility and thermal stability problems in high temperature, concentrated salt solutions.

Super alloys have been developed for high temperature applications, but they are unable to meet the requirements of both the high-temperature strength and the high-temperature erosion–corrosion resistance simultaneously [29]. No metal or alloy is immune to high temperature attack, though some alloy compositions may require a long initiation time before the corrosion process moves from initiation to propagation. One possible way to address these problems is by applying a thin layer of anti-wear and anti-oxidation coatings with good thermal conductivity, such as thermal sprayed nickel or iron based alloyed coatings. The abrasion and corrosion resistance of components can be greatly increased by protective coatings and this is a growing industry of considerable economic importance [9].

A. Preventive Methods for Erosion in Existing Environment are

1. Use of super alloys.
2. Inhibitor.
3. Protective coatings
4. Hardfacings

1. Use of Super Alloys: Alloys that exhibits several characteristics excellent to thermal creep deformation, good surface stability, and resistant to corrosion and oxidation. Most commonly used super alloys are copper based super alloy, Nickel based super alloy.

2. Inhibitor: An Inhibitor is a chemical substance or combination of substances that when present in the environment prevent or reduces corrosion without significant reaction with the component of the environment. For example - NaCrO4 (sodium chromate), NaNO2 (sodium nitrate). The corrosion inhibitor is one of the best know methods of corrosion protection and one of the most useful on the industry. This method is following stand up due to low cost and practice method. [30-33] important researches have being conducted with government investment mainly in large areas such as development construction of new pipelines for shale gas and growth in construction. The focus of these researches has being the inhibitors applications in water and concrete for the protection of metals. [34] Historically, inhibitors had great acceptance in the industries due to excellent anti-corrosive proprieties. However, many showed up as a secondary effect, damage the environment. Thus the scientific community began searching for friendly environmentally inhibitors, like the organic inhibitors. [35-42]. Fig. 7 shows the classification of inhibitors.

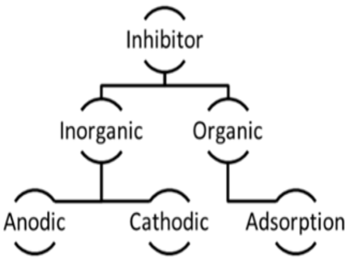

Fig.7 Classification of Inhibitors [43]

a. Inorganic Inhibitors

Anodic inhibitors: They are also known as passivation inhibitors. It act by decreasing anodic reaction, so that block the anode reaction and help the natural reaction of passivation material surface, further due to the forming a layer adsorbed on the material. In general, the inhibitors react along the corrosion product, initially formed, appearing insoluble and cohesive film on the surface of metals [33, 44].

Cathodic inhibitors: During corrosion process, these types of inhibitors prevent the occurrence of the cathodic reaction of the material. The main feature of Cathodic inhibitors are the metal ions that is able to produce a cathodic reaction owing to alkalinity, in such a way that produces the insoluble compounds that precipitate selectively on the cathodic sites. Also this types of inhibitors cause greater cathodic inhibition. [33, 44-45]

b. Organic Inhibitors

Organic compounds used as inhibitors, occasionally, they act as cathodic, anodic or together, as cathodic and anodic inhibitors, nevertheless, as a general rule, act through a process of surface adsorption, designated as a film- forming. Generally the occurrence of molecule exhibits a strong affinity for surface of metals. Compounds exhibit good inhibition efficiency and low environmental risk. [46] These inhibitors build up a protective hydrophobic film adsorbed molecules on the metal surface, which provides a barrier to the dissolution of the metal in the electrolyte. They must be soluble or dispersible in the medium surrounding the metal. [33]

3. Protective Coating for Erosion

A coating can be defined as a layer of material, formed naturally or deposited artificially on the surface of an object made of another material, with an aim of obtaining required technical or decorative properties. A number of protective coatings are present in the market having different properties. Different coatings are used to prevent/reduce the loss of materials by erosion, erosion-corrosion and wear.
Coating Techniques: From a production point of view, following three methods are in current use:

a. Chemical Vapor Deposition (CVD): Chemical Vapor Deposition (CVD) process is a versatile process that can be used to deposit nearly any metal as well as non-metal such as carbon or silicon. The first step is the production of metal vapours. Several chemical reactions can be used: thermal decomposition, pyrolysis, reduction, oxidation, nitridation etc. The main reaction is carried out in a separate reactor. The vapors thus formed are transferred to the coating chamber where the sample is mounted and maintained at high temperature. One of the limitations of the CVD is the high substrate temperature, which in many cases changes the microstructure of the substrate, and another is the size of specimens, often smaller parts are used due to limitation of chamber size.

b. Physical Vapour Deposition (PVD): In physical vapor deposition (PVD) process, the coating is deposited in vacuum by condensation from a flux of neutral or ionized atoms of metals. Several PVD techniques are available for deposition of hard coatings. Among them, cathodic arc vapor (plasma or arc ion plating) deposition, magnetron sputtering (or sputter ion plating), and combined magnetron and arc processes are most widely used techniques to deposit Ti-Al based coatings.

c. Thermal Spraying (Metal Spraying) or Nanostructured Coating: Nanostructured coatings consist of crystalline or amorphous nanophase mixture have recently attracted increasing interests in basic research and industrial applications, because of the possibilities of synthesizing a surface protection layer with unique physical chemical properties that are often not attained in the bulk materials. Nanostructured materials as a new class of engineering materials with enhanced properties and structural length scale between 1 and 100 nm.

d. Thermal Spraying Technology: Thermal spraying is one of the most effective and low cost method to protect the material from wear, high temperature corrosion, stresses and erosion, thus increasing the life of material in use. Thermal spray coatings represent an important and cost effective technique for tailoring the surface properties of engineering components with a view to enhancing their durability and performance under variety of operating conditions. Coatings are used in a wide range of applications such as boiler components, power generation equipments, aircrafts, textile and automobile. Based on the heat source, the thermal spray coating process may be classified as shown in following flow chart, fig. 8.

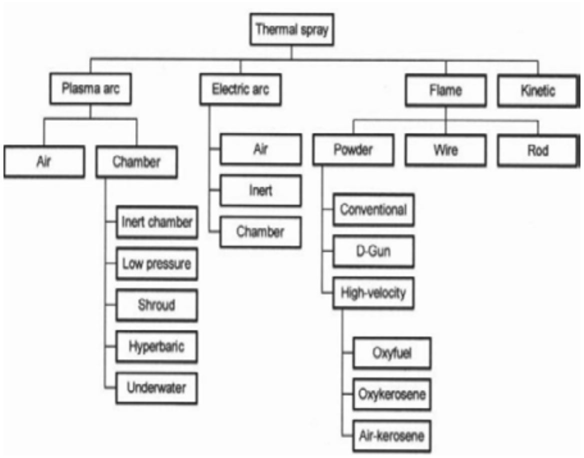

Fig.8 Classification of various thermal spray coating processes. [47]

Due to its several advantages such as low cost, versatility, high processing speed it is most widely used in aircraft engines, thermal power plant, bridge, photo chemical industry, automotives system, chemical process equipment, dies, marine turbines, power generation equipments. It is mainly used to apply coating to a numerous range of materials and machine parts to impart resistance to erosion, corrosion, wear, and cavitation. Except this it provide lubricity, sacrificial wear, electrical conductivity, low or high friction and chemical resistance.

4. Hardfacing

Hardfacing is the process of depositing a material layers over the base metal or substrate either to improve surface characteristics like wear resistance, corrosion resistance and hardness etc. or to get the dimensions of the required size. But before applying any surface deposits for surface enhancement of any engineering component, it is important to understand the working environment under which it works.

a. Hardfacing Deposition Techniques

1. Thermal Spraying
2. Cladding
3. Welding

Thermal Spraying is the process where the material in powder form is sprayed over the substrate by means of spraying gun. These processes are preferred for applications requiring thin, hard coatings applied with minimal thermal distortion of the work piece with good process control. These processes are most commonly use the coating material in the powder form, and almost any material capable of being melted without decomposition, vaporization, sublimation or dissociation can be thermally sprayed.

Cladding is the process in which bulk materials in foil, sheet or plate form is bonded over the substrate to provide triboligical properties. The cladding process are used either where coatings by thermal spraying and welding cannot be applied or for the applications which require surfaces with bulk properties. Since relatively thick sheets can be readily clad to substrate, increased wear protection may be possible compared to thermal spraying and welding. If the coating material is available in sheet form, then cladding may be cheaper than alternative processes, but it is difficult to clad having complex shapes and extremely large sizes.

Welding for hardfacing is preferred over other processes in the applications requiring dense relatively thick coatings (due to extremely high deposition rates) with high bond strength. Welding coatings may be applied to substrate to withstand high temperature. Welding process most commonly use the coating material in wire or rod form. Thus materials that can be easily cast in rods or drawn into wires are commonly deposited. In the Arc Welding the substrate and the coating material must be electrically conductive. Welding processes are most commonly used to deposit primarily various metals and alloys on the metal substrates.

In contrast to thermal spraying processes which does not penetrate the base metal, welding process melt a portion of the surface and this fusion zone mixed or diluted in the weld metal. Mixing of a proportion of the substrate metal with the weld can affect the composition, the microstructure and hence wear resistance.In spite of the use of hardfacing for restoration of the worn out parts to make it usable, this process is also applied for surface modification of new components before being placed into surface. In addition to this hardfacing possesses has the following advantages:

1. Hardfaced components have longer service life as it requires less replacement than ordinary parts.
2. Hardfacing also contributes to the equipment working and producing more units per hour which further increases productivity.
3. Longer service time and less replacements reduces the downtime for the machine and hence its greater availability.
4. Hardfacing improves the hardness and wear resistance properties at reduced costs.
5. There is no need to keep numerous spare when worn parts can be rebuilt.

Hardfacing finds its excessive use to restore the old products at reduced costs to extend its lifetime. This is widely used in Agriculture, Mining, Metallic, Pulp and Paper, Dredging, Foundry, Petroleum, Metal Production, Cement, Concrete, Glass, Railroad, Plastic, Steel Making, Metal Forming, Brick and Crushing industry.

Bulloch *et al.,* [48] reviewed various aspects pertaining to wear processes and hardfacing materials and attempts to clarify the necessary requirements for selection of correct hardfacing materials to mitigate wear processes. It considered the economics of hardfacing material by taking into considerations like cost of repair of replacement, time between scheduled plant shutdowns and financial overheads, wear processes and testing procedures and material selection for wear resistance. The effectiveness of surface treatments and coatings in combating wear were discussed as well as the micro structural influence on wear resistance. Finally outlines for the classification of the various hardfacing materials were assessed.

Wood *et al.,* [49] studied the sand erosion performance of detonation gun applied tungsten carbide/cobalt-chromium coatings. Study was undertaken using a sand/water jet impingement rig. Authors found that the erosion rate of as sprayed compared to sintered tungsten carbide-cobalt chrome was similar for low energy impacts. This reflects the anisotropic microstructure of the thermally sprayed coating with preferred crack propagation parallel to the coating surface followed by crack interlinking and spalling. This is the dominant erosion mechanism present.

Cheng *et al.,* [50] emphasized that erosion is the serious problem in many engineering systems, including steam and jet turbines, pipelines and valves used in slurry transportation of matter, and fluidized bed combustion systems.

Sundararajan *et al.,* [51] categorized large varieties of detonation sprayed coatings and each coating over a range of process parameters. These coatings are characterized in terms of phase content and distribution, porosity, micro hardness and evaluated for erosion, abrasion and sliding wear resistance. From the results it is found that the hardness and tribological properties of thermal sprayed coatings are more strongly affected by the process parameters themselves rather than micro structural parameters such as phase content and distribution, porosity, etc.

Grewal *et al.,* [52] used Detonation-Gun Spray for developing protective coatings of almost any material like oxides, carbides, metals, hard alloys and powder of composite material onto mild steel and other EN series.

Antonov *et al.,* [53] investigate the effect of oxidation on the erosive behaviour of boiler steels in a cyclic mode. Several parameters are proposed and Tests were performed using specially developed device allowing testing in either oxidizing or protected atmosphere the assessment is done on their applicability to describe the erosion–oxidation phenomena under different impact angles. It is shown that under specific conditions oxide scales provide improved wear resistance for some steels, particularly austenitic ones, that enables reduced material losses.

These problems can be overcome by either changing the material or altering the environment or by separating the material surface from the environment. The distinct investigations have been carried to overcome the erosion-corrosion problems of boiler tubes and found that erosion resistant coating and hard facing are effective methods to resist hot corrosion.

V. CONCLUSIONS

Hot corrosion and erosion are serious problems in power generation equipment, in gas turbines for ships and aircrafts and in other energy conversion and chemical process systems and should be either totally prevented or detected at an early stage to avoid catastrophic failure. Application of a proper combination of preventive approaches should lead, in practice, to a significant decrease in the number of failures due to hot corrosion. Hot corrosion and Erosion preventive methods to the existing environment are (a) change of metal i.e. use of super alloy (b) use of inhibitors and (c) use of coatings (d) use of hardfacing. From the literature it is found that hardfacing and coating proved to reduce maximum hot corrosion.

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