

applications in water and concrete for the protection of metals. [34] Historically, inhibitors had great acceptance in the industries due to excellent anti-corrosive properties. 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.

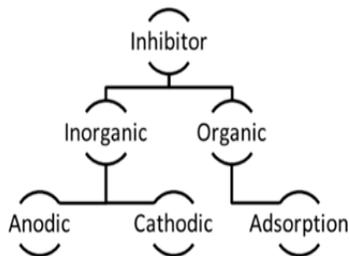


Fig.7 Classification of Inhibitors [43]

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.

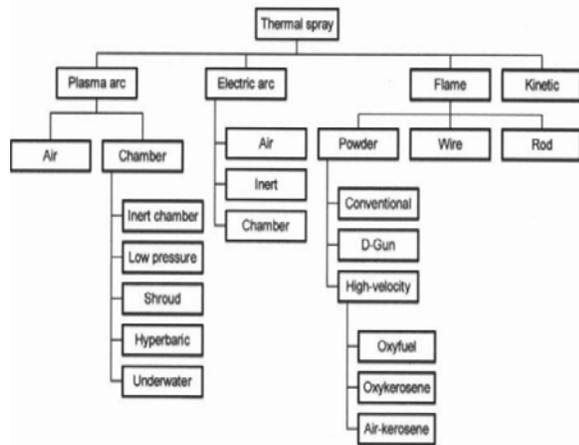


Fig.8 Classification of various thermal spray coating processes. [47]

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

tribological 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 or 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.

REFERENCES

- [1] J. K. Stein, S. B. Schorr and R. A. Marder, "Erosion of Thermal Spray MCr Cr C Cermets Coatings", *Wear*, Vol. 224, pp. 153-159, 1999.
- [2] H. V. Hidalgo, J. Verela, C. A. Menendez and P. S. Martinez, "High Temperature Erosion Wear of Flame and Plasma Sprayed Nickel-Chromium Coatings Under Simulated Coal-Fired Boiler Atmospheres", *Wear*, Vol. 247, pp. 214-222, 1999.
- [3] R. Bellman and A. Levy, "Erosion mechanism in ductile metals", *Journal of Wear*, Vol. 70, pp. 1-28, 1981.
- [4] M. Parsi, K. Najmi, F. Najafifard, S. Hassani and McLaury, "A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications", *Journal of Natural Gas Science and Engineering*, Vol. 21, pp.850-873, 2014.
- [5] D. Chase, E. Rybicki and J. Shadley, "A model for the effect of velocity on erosion of N80 steel tubing due to the normal impingement of solid particle", *Journal of Energy Resource. Tech.*, Vol. 114, pp.54-64, 1992.
- [6] I. Hutchings, "Some comments on the theoretical treatment of erosive particle impacts", in *Proc. of the 5th Int. Conf. on Erosion by Liquid and Solid Impact*, pp. 36-41, 1980.
- [7] D. Andrews, "An analysis of solid particle erosion mechanisms", *J. Phys. D Appl. Phys.*, Vol. 14, pp. 1979-1991, 1981.
- [8] S. Jahanmir, "The mechanics of subsurface damage in solid particle erosion", *Wear*, Vol. 61, pp. 309-338, 1980.
- [9] S. Srinivasan, R. O. Scattergood, "Effect of erodent hardness on erosion of brittle materials", *Wear*, Vol. 128, No. 2, pp.139-152, 1988.
- [10] G. Sundararajan, "A comprehensive model for the solid particle erosion of ductile materials", *Wear*, Vol. 149, pp. 111-127, 1991.
- [11] I. Kleis and P. Kulu, "Solid Particle Erosion Occurrence, Prediction and Control", *Springer*, Verlag London Limited, Library of Congress Control Number: 2007937988, 2008.
- [12] V. S. Sooraj and V. Radhakrishnan, "Elastic impact of abrasives for controlled erosion in fine finishing of surfaces", *ASME J. Manuf. Sci. Eng.*, Vol.135, pp.125-132, 2013.
- [13] M. Dular, B. Stoffel and B. Sirok, "Development of a Cavitation Erosion Model", *Wear*, 261, pp. 642-655, 2006.
- [14] N. Fujisawa, K. Wada and T. Yamagata, "Numerical Analysis on the Wall- Thinning Rate of Bent Pipe by Liquid Droplet Impingement Erosion", *Engg. Failure Analysis*, Vol. 62, pp. 306-315, 2016.
- [15] B. Mann and V. Arya, "Abrasive and Erosive Wear Characteristics of Plasma Nitriding and HVOF Coatings: Their Application in Hydro Turbines", *Wear*, Vol. 249, pp. 354, 2001.
- [16] H. S. Grewal, S. Bhandari and H. Singh, "Parametric Study of Slurry-Erosion of Hydro turbine Steels with and without Detonation Gun Spray Coatings using Taguchi Technique", *Journal of Metall. Mater. Trans.*, Vol. 43, pp. 33-37, 2012.

- [17] H. S. Grewal, H. Singh and A. Agrawal, "Micro structural and Mechanical Characterization of Thermal Sprayed Nickel–Alumina Composite Coatings", *Journal of Surf. Coating Technology*, Vol.216, pp.70-78,2013.
- [18] A. A. Kasem, M. Y. Abd-elrhman, M. K. Emara and M. S. Ahmed, "Design and Performance of Slurry Erosion Tester", *Journal of Tribology*, Vol.132, pp.1-10, 2010.
- [19] R. S. Morea, V. D. Bhattb and V. J. Menghani, "Recent Research Status on Erosion Wear – An Overview", *Materials Today: Proceedings*, Vol. 4, pp.257–266, 2017.
- [20] L. J. He, C. K. Chen, C. C. Chen, A. Leyland and A. Matthews, "Cyclic Oxidation Resistance of Ni-Al Alloy Coatings Deposited on Steel by a Cathodic Arc Plasma Process", *Journal of Surf. Coating Technology*, Vol. 135, pp. 158-65, 2001.
- [21] S. A. Khana, and K. S. Jha, "Degradation of materials under hot corrosion conditions", *Journal of Trans. Indian Inst. Met.*, Vol. 51, pp. 279-90, 1998.
- [22] N. Eliaz, Shemesh and M. R. G. Latenision, "Hot corrosion in gas turbine components", *Journal of Engineering failure analysis*, Vol. 9, pp. 31-43, 2002.
- [23] H. Edris, G. D. McCartney and J. A. Sturgeon, "Micro-structural Characterization of HVOF Sprayed Coatings of Inconel 625", *Journal of Mater. Sci.*, Vol. 32, pp.863–868, 1997.
- [24] P. Hancock, "Vanadic and chloride attack of Super alloys", *Material Science Technology*, Vol. 3, pp. 536–544, 2006.
- [25] J. Stringer, "High Temperature Corrosion of Superalloys", *Material Science and Technology*, Vol.3, pp. 482–493, 1987.
- [26] R. J. Nicholls, "Designing Oxidation-Resistant Coatings, *JOM*, Vol. 52, pp. 28–35, 2000.
- [27] H. G. Meier, "A Review of Advances in High-Temperature Corrosion", *Material Science and Engineering*, Vol. 120, pp. 1–11, 1989.
- [28] J. Stringer, "High Temperature Corrosion of Superalloys", *Material Science and Technology*, Vol. 3, pp.482–493, 1987.
- [29] M. Salasi, T. Sharabi, E. Roayaei and M. Aliofkhazraei, "The electrochemical behaviour of environment-friendly inhibitors of silicate and phosphonate in corrosion control of carbon steel in soft water media", *Materials Chemistry and physics*, Vol. 104, Issue 1, pp. 183-190, 2007.
- [30] S. M. Al-Otaibi, M. A. Al-Mayouf, M. Khan, M. M. Mousa and Z. H. Alkathlan, " Corrosioninhibitory action of some plant extracts on the corrosion of mild steel in acidic media", *Arabian Journal of Chemistry*, pp. 1-7,2012.
- [31] B. I. Obot, O. N. Obi-Egbedi and A. S. Umoren, "Antifungal drugs as corrosion inhibitors for aluminium in 0.1 M HCl", *Journal of Corrosion Science*, Vol. 51, Issue 8, pp. 1868-1875, 2009.
- [32] A. Yıldırım, and M. Çetin, "Synthesis and evaluation of new long alkyl side chain acetamide, isoxazolidine and isoxazoline derivatives as corrosion inhibitors", *Journal of Corrosion Science*, Vol. 50, Issue 1, pp.155-165, 2008.
- [33] [33] V. Gentil, "Corrosão, 4ª ed., Rio de Janeiro: LTC", pp. 55-75, 2003.
- [34] P. Finishing, "pfonline", Finishing Industry, 03 06 2013. [Online]. Available:<http://www.pfonline.com/news/us-demand-for-corrosion-inhibitors-to-reach-25-billionin-2017>. [Accessed: 7 Oct. 2013].
- [35] Negm, A. Nabel, Kandile, G. Nadia, Badr, A. Emad and A. Mohammed, "Gravimetric and electro chemical evaluation of environmentally friendly nonionic Corrosion Inhibitors -Principles, Mechanisms and Applications", *Journal of Corrosion Science*, Vol. 65, pp. 94-103, 2012.
- [36] M. A. Abdel- Gaber, A. B. Abd-El-Nabey, E. Khamis and E. D. Abdel-Khalek, " A natural extract as scale and corrosion inhibitor for steel surface in brine solution Desalination", Vol. 278, Issue 1-2, pp. 337-342, 2011.
- [37] M. Salasi, T. Sharabi, E. Roayaei and M. Aliofkhazraei, "The electrochemical behaviour of environment-friendly inhibitors of silicate and phosphonate in corrosion control of carbon steel in soft water media", *Materials Chemistry and physics*, Vol. 104, Issue 1, pp. 183-190, 2007.
- [38] G. Blustein and J. A. J.Romagnoli, "Zinc basic benzoate as eco-friendly steel corrosion inhibitor pigment for anticorrosive epoxy-coatings", *Colloids and Surfaces, Physicochemical and Engineering Aspects*, Vol. 290, Issue 1-3, pp. 7-18, 2006.
- [39] P. Bommersbach, Alemay-Dumont, P. J. Millet and Normand, "Formation and behaviour study of an environment -friendly corrosion inhibitor by electrochemical methods", *Electrochemical Acta*, Vol. 51, Issue 6, pp. 1076- 1084, 2005.
- [40] A. Lecante, F. Robert, A. P. Blandinières and Roos, "Anti-corrosive properties of S. tinctoria and G. ouregou alkaloid extracts on low carbon steel", *Current Applied Physics*, Vol. 11, Issue 3, pp. 714-724, 2011.
- [41] Radojic, K. Berković, S. Kovac and Vorkapic-Furac, "Natural honey and black radish juice as tin corrosion inhibitors", *Corrosion Science*, Vol. 50, Issue 5, pp. 1498-1504, 2008.
- [42] C. P. Okafor, E. M. Ikpi, E. I. Uwah and E. E. Ebenso, "Inhibitory action of Phyllanthus amarus extracts on the corrosion of mild steel in acidic media", *Corrosion Science*, Vol. 50, Issue 8, pp. 2310-2317, 2008.
- [43] F. A. Galio, and G. C. Dariva, "Corrosion Inhibitors- Principles, Mechanism and Applications", [Online]. Available: <http://dx.doi.org/10.5772/57255>, pp. 365-376, 2014.
- [44] R. P. Roberge, "Handbook of corrosion engineering, New York: Mc Graw Hill Handbook", 1999.
- [45] D. Talbot, "Corrosion science and technology, Florida: CRC Press",2000.
- [46] Aprael S. Yaro, Anees A. Khadom, K. Rafal and Wael, "Apricot juice as green corrosion inhibitor of mild steel in phosphoric acid", *Alexandria Engineering Journal*, vol. 52, issue 1, pp. 129-135, 2013.
- [47] S. Amin and H. Panchal, "A Review on Thermal Spray Coating Processes", *International Journal of Current Trends in Engineering and Research*, Vol. 2 Issue 4, pp. 556 – 563, 2016.
- [48] J. H. Bulloch and J. L. Henderson, "Some considerations of wear and Hard facing materials", *International Journal of Pressure Vessel and Piping*, Vol. 46, pp. 251–267, 1991.
- [49] R. J. K. Wood, B.G. Mellor and M. L. Binfield, "Sand erosion performance of detonation gunapplied tungsten carbide/cobalt-chromium coatings", *Wear*, Vol. 211, Issue 1, pp. 70-83, 1997.
- [50] Y. B. Cheng, Y. Zhang and S. Lathabai, "Erosion of Aluminium Ceramics by Air- and Water-Suspende Gernet Particles", *Wear*, Vol. 240, pp. 40-51, 2000.
- [51] G. Sundaranjan, Sen and D. Sivakumar, "The tribological behaviour of detonation sprayed coatings: the importance of coating process parameters", *Wear*, Vol. 258, pp. 377-391, 2005.
- [52] J. S. Grewal, P. J. Singla, and V. Chawla, "A survey of the detonation gun sprayed wear resistant coatings", *National Conference of Mechanical and Material engineering*, pp. 55-61, 2010.
- [53] Antonov Maksim, Renno, V. Huttrenen-Saarivirta, Irina Hussainavo, AhtoVallikin, Martvn Lelis and Jelena Priss., "Effect of oxidation on erosive wear behaviour of boiler steels", *Tribology International*, pp. 222-232, 2012.