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A Review of Coating Methods for Surface Protection

Md Sarfaraz Alam[1] , **Kumar Jyotiraditya**[2] , **Saurabh Priyadarshi**[3]

[1]Assistant Professor, Department of Mechanical Engineering, Sershah Engineering College, Sasaram, Bihar, India

[2]Assistant Professor, Department of Mechanical Engineering, Bhagalpur College of Engineering, Bhagalpur, Bihar, India

[3]Assistant Professor, Department of Mechanical Engineering, Government Engineering College, Gopalganj, Bihar, India

Abstract- For various coating applications, a broad range of coating techniques and materials are available, all of which have the same general goal of shielding a component or structure from mechanical or chemical harm. Reduced manufacturing costs are one advantage of this protective feature since it eliminates the need to fabricate new parts. Hard and rigid metallic alloys, ceramics, bio-glasses, polymers, and tailored plastic materials are among the coating materials that are available, offering designers a wide range of options for long-lasting protection. Many techniques have been developed and studied up to this point, including thermal spraying, sol-gel, micro-arc oxidation, physical/chemical vapor deposition, and electrode position. Despite the benefits that each of these procedures offers, there are always issues that restrict their use. However, by using the advantages of each process in a multi-method coating, there are several ways to address the shortcomings of coating procedures. These coating techniques are contrasted and categorized in this article. Future developments might lead to improved protective properties through the use of increasingly sophisticated coating methods and materials.

Keywords— *Surface Modification, Sol–Gel, Thermal Spray, Vapor Deposition, Reduced Manufacturing Costs.*

Introduction

Structures and pieces made of metal are made for certain uses. Some significant restrictions on material selection must be satisfied before these parts may be fabricated. The following are some examples of these limitations: body composition; mechanical characteristics (tension, compression, yield, torsion, fatigue, bending, and creep); desired functionality (wear resistance, hydrophobicity, friction properties); thermal characteristics (thermal expansion and heat flux conductivity); electrical conductivity; dynamic load bearing (vibrations, high-speed rotation); and corrosion resistance. Other factors that need to be taken into account are availability, pricing, toxicity, and safety of the materials. In order to manufacture mechanical components and structures, the latter category is crucial in completing the material selection procedures. For example, although it is well known that silver has high electrical conductivity values, producing large quantities of silver for electrical conductivity applications is prohibitively expensive. Shape memory effect (SME) and superelasticity (SE) are well-known properties of NiTi alloys that are helpful for creating novel actuators. Furthermore, these alloys offer excellent biocompatibility since they may be employed as bone implants in conjunction with SME, SE, or both to create novel biomedical devices for internal human microsurgeries. However, Ni ions are released as byproducts of the corrosion process of NiTi in physiological settings, and these compounds are hazardous and poisonous to living things. High thermal and electrical conductivity copper is used in numerous applications, including the brazing of sophisticated materials, although it has poor stiffness and wear resistance. Because copper is very susceptible to wear mechanisms, the endurance of the mechanical parts in the case of copper rotating cooling fins is greatly reduced. Various techniques, including heat treatment, alloying procedures, and coatings, have been proposed to address these problems and improve material qualities for particular purposes. The greatest amount of material improvement is seen in coating procedures among these options since coating layers may overlook material shortage and lower costs because their thickness seldom exceeds micrometres. This implies that a larger variety of substrate materials may be coated with a lower amount of material. Several qualities, including improved wettability, hydrophobicity, improved surface hardness, altered surface texture, and resistance to corrosion and wear, may be obtained from coatings. The vast range of demands and applications in many industries has led to the availability of a broad array of coating processes. Numerous distinct on-line and offline factors are involved in these processes, which yield a wide range of results in terms of material microstructure, appropriateness, durability, and efficacy. Nonetheless, depending on the required functionality, coating techniques might be helpful in some applications; the most crucial ones being wear and corrosion protection. While the corrosion process reduces the mechanical qualities of the materials, the corrosion products are discharged in various forms that might have detrimental side effects in some applications or create an even more harsh corrosive environment. Different coating materials have different deposition methods, which must be studied to determine the benefits and drawbacks for the intended use. While numerous techniques exist, only a select number rank among the most useful and efficient; they include sol–gel, thermal spray, micro-arc oxidation (MAO), physical vapour deposition (PVD), chemical vapour deposition (CVD), and polymer coatings. Since each of these techniques offers a variety of deposition techniques, materials, second phases, thicknesses, and densities, they are all appropriate for a range of applications. Therefore, for a particular type of coating, considerable consideration must be given to mechanical stability, corrosion characteristics, biocompatibility (for biomedical applications), and improvement of material behaviour. Even while coating technologies are used to deliver the aforementioned advantages, they have drawbacks that reduce their dependability. The most important adverse effects to take into account are the following: destructive effects of loose atmospheric protection (e.g., penetration of inclusions and contaminations into the substrate), negative thermal effects (e.g., distortion, crack, delamination, etc.), and properties of the coating materials (e.g., melting point, availability in different forms of foils, powders, rods, biocompatibility, etc.).

Research Concerning Surface Coatings

Current research on surface coating focuses on using various coating methods, parameters, different base materials and materials to be coated. Lozano D.E., Mercado-Solis R.D. (2009) evaluated wear performance of the new hypereutectic Al-Si-Cu alloy using Pin- on-disc tribometer. Modern engine blocks use grey iron liners from the engine bore; however a new hypereutectic Al alloy was developed to eliminate grey iron liners from engine block. Wear evaluation was carried out at different loading conditions, various sliding speeds and various sliding distances under lubricated and un-lubricated conditions.

Bobzin K., Lugscheider E. (2007) examined magnetron sputtered three (Cr 1-x Alx) N coatings on their tribological characteristics with different aluminum contents (x = 0; 0.23; 1) .The tests were performed on BoD tribometer. The ceramics Al2O3 and Si3N4 were used as counterpart materials. The counterpart wear for Al2O3 was less than for Si3N4. On the contrary the highest wear rates of coated samples were measured for Al2O3. With regard to coatings, Cr 0.77 Al 0.23 N showed the lowest wear rates in all cases, though the friction coefficient of Cr 0.77 Al 0.23 N against Si3N4 was the highest.

Shaffer S.J., Rogers M. J. (2007) assessed the tribological performance of a variety of coatings under un-lubricated sliding conditions. Coatings types investigated include: TiCN, PTFE filled resin-bonded coatings, electro less nickel- cobalt alloy coatings, ferritic nitro-carburizing treatment etc. Substrate included medium carbon steel, D2 tool steel and 6061-T6 aluminum. The tests were run using a cylinder-on-flat geometry with self-mated coatings in both reciprocating and unidirectional conditions. These tests ranked the tribological performance of the coatings using both coefficient of friction and wear coefficient. The best performing samples were tested up to total sliding distance of 3.6 km.

Sidhu et al (2003) studied and concluded that the thermal sprayed Ni3Al coatings on boiler tube steels was very effective in decreasing corrosion rate in air and molten salt at 900ºC in case of ASTM-SA210 grade A1 steel and ASTM-SA-213-T11 type of steel whereas coating was least effective for ASTM-SA-213-T22 steel. They further proposed that uncoated ASTM-SA-213-T22 steel showed very poor resistance to hot corrosion in molten salt environment with spalling of oxide scale.

Singh et al (2003) investigated the NiCrAlY, Ni-20Cr, Ni3Al and satellite-6 coatings on Fe-based super alloy at temperature 900 ºC in the molten environment under cyclic conditions. After performing XRD, SEM/EDAX and EPMA, they found that all these coating showed better resistance to hot corrosion as compared to that of uncoated super alloy and NiCrAlY was found to be most protective followed by Ni-20Cr coating. The Ni3Al coating was also effective in decreasing the weight gain to about one third as compared to uncoated super alloy. They further found that satellite coating was least effective but still decreases the weight gain to about 60% that of uncoated super alloy. The formation of oxides and spinels of Ni, Al, Cr or Co may be contributing to the development of hot corrosion resistance.

Gulene & Kahraman (2002) examined that the abrasive wear rate can often be reduced by the application of hard materials. The transition from low wear to high wear with increasing hardness of the abrasive is very instructive and abrasive wear resistance of flame sprayed coatings observed to be dependent on the chemical composition and characteristics of coating materials and coating condition.

Gitanjali et al (2000) reported that by controlling the various process parameters (air /fuel ratio, temperature, pressure, etc.) of boiler and gas turbines were also useful to some extent in combating oil ash corrosion. The low excess of combustion air can control hot temperature of boilers to some extent. As a matter of fact excess of oxygen promotes formation of SO3 and V2O5 (melting point 675ºC) instead of lower oxides V2O3-V2O4 (melting point 2000ºC). The industrial practice generally does not allow operating with low excess of combustion air, consequently the use of additives turns out to be the only effective means to prevent corrosion at elevated temperatures.

Wilson S., Alps A.T. (1998) performed dry sliding wear experiments using TiN coatings on AISI M2 high-speed steel substrate. Wear rates, coefficients of friction, and temperatures of were measured as a function of load. Three wear regimes were identified; transfer and build up of oxidized pin debris on the coating (20N), increased polishing damage and brittle spallation failure of the TiN (50-100N), a sharp transition to plastic deformation microploughing of TiN (>100N) which coincided with critical steady state temperature of 160 degrees. Softening of TiN above this temperature leads to rapid wear and exposure of substrate material.

Surface Coating Methods

Surface coating methods are classified as under:

(i) Thermal Spraying (Metal Spraying)- It is a collection of procedures that include heating a feedstock material and launching droplets or individual particles onto a surface. As sprayed particles hit the surface, they cool and accumulate into a laminar structure, splat by splat, to produce the thermal spray coating. The primary components of a detonation gun unit are a double-walled barrel, a combustion chamber, a powder feeder, and control panels for managing gas operation and flow. An suitable manipulator is also included in the setup to grip the work piece and regulate its movements. A tiny quantity of powder and an explosive combination of oxygen and acetylene are placed inside a barrel. A spark plug is used to ignite the mixture. The entrained powder particles are heated and accelerate by a detonation wave upon ignition. It melts and propels the particles onto the substrate by means of sporadic explosions as opposed to a continuous combustion process. Nitrogen is pumped out of the barrel following each detonation. It is imperative that all leftover "hot" powder particles be removed from the chamber in order to prevent the explosive combination from detonating unevenly. One cycle of explosion is therefore finished. The aforementioned process is carried out repeatedly at a certain frequency until the necessary coating thickness is deposited.

(ii) Chemical Vapor Deposition (CVD)- In an active (heat, light, or plasma) environment, gaseous reactants dissociate and/or undergo chemical reactions, and a stable solid product is subsequently formed. The deposition process involves the creation of powders or films, respectively, as a result of heterogeneous chemical reactions that take place on or near a heated surface, as well as homogeneous gas phase reactions that take place in the gas phase. Benefits of the Chemical Vapour Deposition (CVD) technique include: the capacity to create materials that are incredibly pure and dense. produces films that are homogenous, adhere well, and have acceptable repeatability at a respectably high deposition rate. CVD has good throwing power and operates in a non-line-of-sight manner. As a result, it may be applied to deposit films with strong conformal coverage and coat complexly shaped components consistently. By adjusting the parameters of the CVD process, it may regulate the crystal structure, surface morphology, and orientation of the CVD products. The rate of deposition is easily adjustable.For microelectronic applications, epitaxial thin film growth is best achieved at low deposition rates. However, a fast deposition rate which can be higher than tens of millimetres per hour is preferable for the deposition of thick protective coatings. Techniques like plasma spraying are the only ones that significance.

(iii) Physical Vapor Deposition (PVD)- Its foundation is the process of removing atoms off surfaces and collecting them either atomic or ionic to coat a submaterial surface by sloping or evaporating materials in a vacuum. Using the PVD process, coating material is transferred from a solid, liquid, or gas source to the surface in the form of atoms, molecules, or ions. This is accomplished physically rather than chemically. On the primary material surface, which is too cold for CVD coating (50,500 °C), chemical reactions can occur, but they are not required. The fact that PVD operation is carried out at comparatively lower temperatures is more intriguing. Additionally, the microstructure and characteristics of the primary material remain unaltered upon the completion of the coating. Three techniques are used in the PVD method: evaporating, dispersing, and ionic coating.

Dependable Coating Techniques

In a variety of industries, from the aerospace and automotive sectors to the small biomedical devices and implants inside the human body, coating procedures offer protection to a particular component or area of a structure exposed to abrasive and hostile conditions.

(i) Physical Vapor Deposition (PVD) Coating- The PVD method is well-known for providing thin protective layers and corrosion and wear resistance to materials exposed to corrosive environments. Its applications span from industrial components to ornamental pieces. This approach has the benefit of allowing the coating layers' mechanical, corrosion-resistant, and cosmetic qualities to be changed as needed. Generally speaking, PVD is a high vacuum process in which liquid or solid materials transition to a vapour phase, then metal vapour condensation results in the formation of a thick, solid film. The two most well-known forms of PVD are evaporation and sputtering. Multilayered coatings are always required since PVD produces thin coating layers, therefore material selection needs to be done with great care. In addition to its aesthetic usage, a lot of PVD-coated items are used in high-wear applications where they abrade the surface and remove the coating layer. This process causes the components' resistance to corrosion to decrease, increasing their susceptibility to corrosive conditions. A schematic depiction of many kinds of electron beam PVD devices is shown in Figure 1.

(ii) Chemical Vapor Deposition (CVD) Coating- CVD is a different kind of vapour deposition. The semiconductor industry uses this technique extensively because it produces a strong, high-quality, and very resistant coating layer on any substrate while subjecting it to a high vacuum. Mechanical parts that are in regular contact and require protection against wear and corrosion can be treated using CVD. In this procedure, a set of volatile material precursors would be introduced to the substrate, sometimes referred to as a wafer, and a chemical reaction would result in the creation of a deposition layer on the material's surface. Even though the vacuum pump's continuous airflow removes most of the chemical processes' byproducts, some may still stay in the chamber. Figure 2 shows a schematic of the CVD setup. The heaters maintain a temperature high enough to promote the chemical interaction between the vaporised materials and substrate, while the vaporised CVD materials are pumped from the right side.

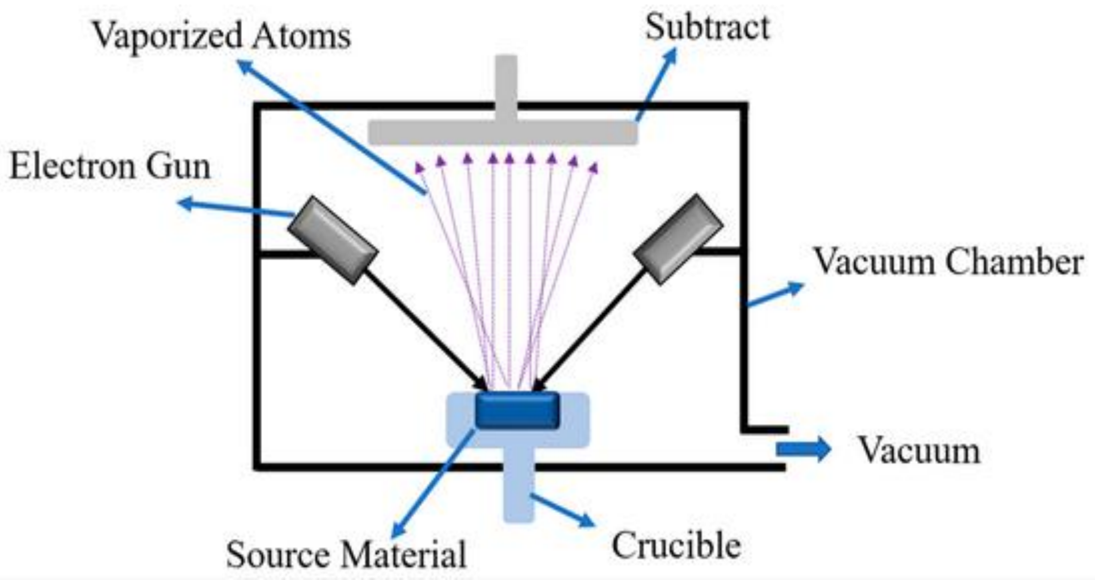

Figure 1- Schematic view of a physical vapor deposition (PVD) machine using electron beam as the heat source

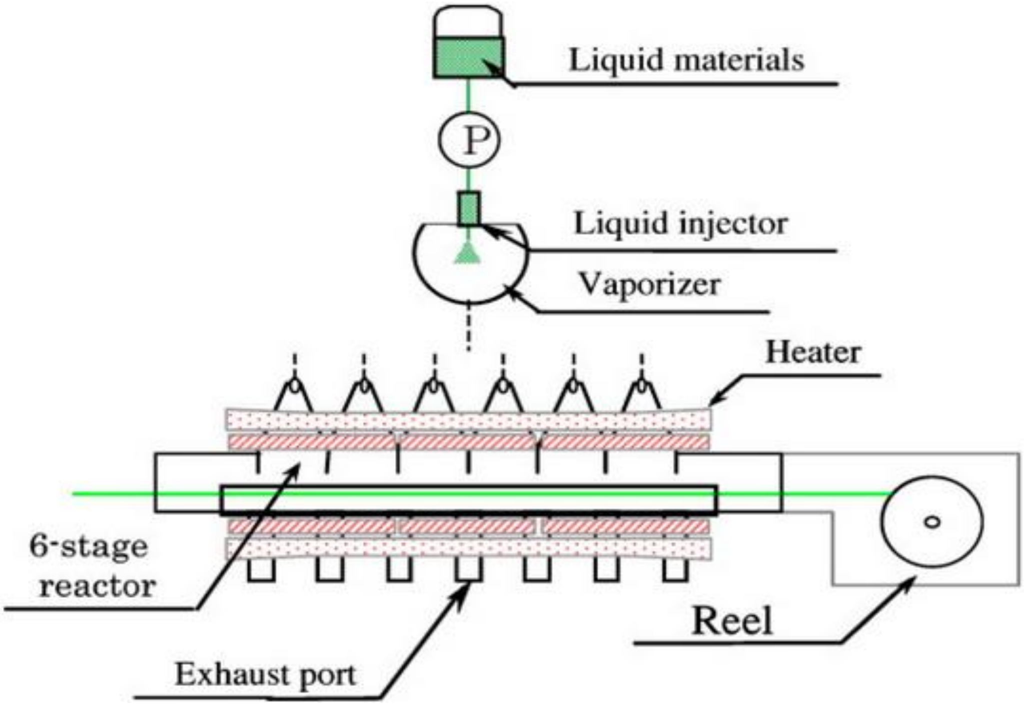

Figure 2- Schematic chemical vapor deposition (CVD) setup, mechanical parts, and operation mechanism

(iii) Micro-Arc Oxidation (MAO) Coating- In terms of the makeup of coating layers, the MAO technique is regarded as a flexible coating method. Figure 3 shows the schematic of the procedure. In general, MAO creates micro-arcs as plasma channels by using a large voltage differential between the anode and cathode. Depending on the strength of the micro-arcs, some of the substrate is melted when these arcs strike it. Concurrently, the pressure inside the plasma channels decreases, facilitating the coating materials' deposition on the substrate surface in the working electrolyte. Oxides are produced by a chemical reaction of oxidation brought on by the oxygen present in the electrolyte and are deposited on the substrate materials' surface. The ability to mix desired elements and compounds as a solute in the working electrolyte gives this technique its versatility. Al, Mg, Ti, and their alloys are currently the materials that are coated with MAO the most frequently. The most crucial property of a layer treated with MAO is its high resistance to corrosion. Furthermore, this coating layer offers significant bone ingrowth when produced on biomedical implants and fixations because of its porous nature.

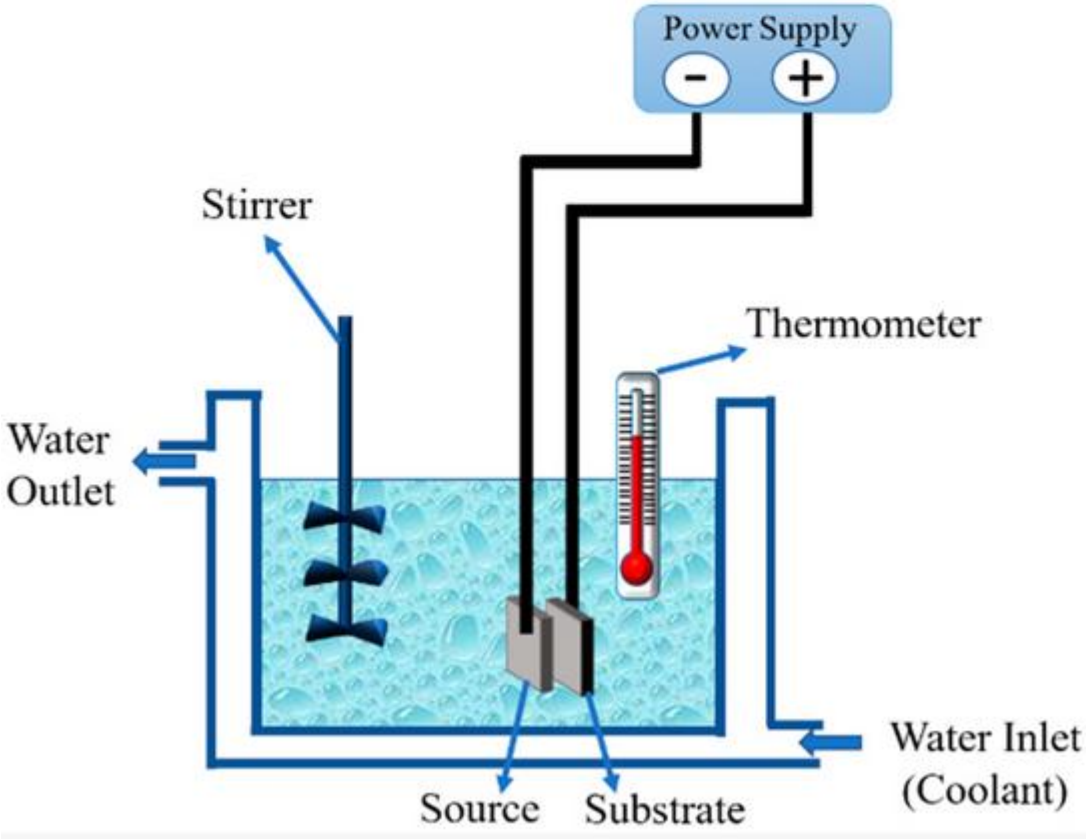

Figure 3- Schematic view of micro-arc oxidation (MAO) process

Conclusion

Several factors must come into play for a coating to deposit well on a substrate: the feedstock form (powder, wire, rods, precursors, etc.), the substrate materials, the deposition techniques, and the deposition materials. Nonetheless, as they deal with the chemical modification of materials and the alloying of composition components in the coating layer, the deposition processes are the most crucial ones. Additionally, selecting the optimal alternative for deposition is simple and depends on the properties of various feedstock and substrate materials. Physical/chemical vapour deposition (PVD/CVD), micro-arc oxidation (MAO), electrodeposition (i.e., electrolytic deposition (ELD) and electrophoretic deposition (EPD)), sol–gel, and various thermal spraying processes (i.e., HVOF, plasma, cold, warm, and arc wire spraying) are the most effective and extensively researched deposition methods. The aforementioned techniques employ distinct mechanisms to deposit particular types of materials onto substrates; hence, the selection of material is crucial to achieving the maximum coating effectiveness. In order to transform the feedstock from a solid state into a liquid or semisolid state in the forms of particles, droplets, and clusters, several procedures employ heat sources. While some deposit materials without undergoing a chemical change of state, others employ the difference in electrochemical charges between the poles. The substrate materials, feedstock, and deposition method all affect the thickness, microstructure, and usefulness of the coating layers. Furthermore, certain techniques are limited to the use of conductive metallic feedstocks, whilst other procedures are capable of depositing ceramics, polymers, and metallic alloys independent of their physical characteristics.

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