

An Overview of Surface Coating Methodologies and Their Use in Technical Materials

Sanjay Kumar Awasthi^{1,*}, Kamal Sharma¹, Aayush Gupta²

Abstract

To safeguard the product or structure against chemical harm, a variety of procedures and materials can be applied in coating applications today. Nowadays, coatings are used extensively in manufacturing all over the world to increase efficiency and reduce expenses two factors that are essential to preserving the sector's profitability. Coated materials have greater strength compared to uncoated materials. A variety of materials, including bio glass, polymers, ceramics, strong and hard metals, and plastics, are accessible to designers as straightforward ways to provide long-term security. Physical/chemical vapour deposition, sol gel, thermal spray, micro arc oxidation, and electro deposition are only a few of the numerous methods that have been documented and studied thus far. This review study brought together recent advancements in the investigation of various functional coating categories, with an emphasis on their uses in intelligent and green buildings. Phase change materials (PCM) coatings and coatings designed to reduce surface solar radiation were among them. Additionally, they contained photo catalytic, hydrophilic, and hydrophobic coatings. High hardness, UV scattering, and homogeneous dispersion at the nanoscale are integrated with the protective properties of conventional coating systems. The current state of nanocoating is examined in this work along with a nanocoating system based on graphene, carbon nanotubes, titanium dioxide, and zinc oxide. At last, a photo of the nanocoating is displayed.

Keywords: Coatings, surface modification, thermal spray, sol-gel, and vapour deposition

INTRODUCTION

A product used to alter the colour, gloss, damage resistance, or top surface of other materials, such as antibiotics, or change permeability without altering the goods volume is referred to as a “coating.” For certain purposes, mechanical structures and parts are created. Several strict criteria for material selection must be satisfied before making these pieces. Physical qualities, mechanical properties (such as stress, compression, yield, torsion, fatigue, bending, and penetration), performance demands (such as wear resistance, hydrophobicity, and frictional strength), and thermal strength (such as thermal expansion) are all impacted by these restrictions. Electrical conductivity, resistance to corrosion, dynamic stress (such as vibration and high-speed spinning), and conduction heat flow. Further consideration must be given to aspects including material availability, price, safety, and toxicity. For instance, it is well known that silver has excellent electrical conductivity values, but producing significant amounts of silver for such uses is prohibitively expensive [1]. Copper has high heat conductivity and electrical conductivity, making it a good material for brazing complex materials, but it also has a low stiffness and wears resistance. The development of novel actuators can benefit from the super elasticity (SE) and shape memory effect (SME) of NiTi alloys, which are widely

*Author for Correspondence

Sanjay Kumar Awasthi
E-mail: sanjay.mech.jmi@gmail.com

¹Professor, Department of Mechanical Engineering, GLA University, Mathura, Uttar Pradesh, India

²Assistant Professor, Department of Mechanical Engineering, GLA University, Mathura, Uttar Pradesh, India

Received Date: July 17, 2024

Accepted Date: July 29, 2024

Published Date: October 08, 2024

Citation: Sanjay Kumar Awasthi, Kamal Sharma, Aayush Gupta. An Overview of Surface Coating Methodologies and Their Use in Technical Materials. Journal of Polymer & Composites. 2024; 12(Special Issue 6): S19–S35.

acknowledged [2]. Copper's resistance to wear mechanisms means that in the case of rotating fins, the dependence on mechanical components is greatly reduced [3]. Many methods, including as heat treatment, alloying, and coating, have been proposed to overcome these problems and improve properties. Based on cost savings and the fact that defects are rarely larger than a micron, coating technique has the best percentage in the literature for this process. It is therefore unnecessary to manufacture numerous materials on various substrates. The method's capacity to harden, alter roughness, improve wettability and hydrophobicity, and other properties can offer numerous benefits, including [4]. There are numerous layers as a result of the variety of uses and needs in various sectors. However, depending on the performance needed, coating technology is effective in several applications, most notably corrosion prevention and wear protection [5]. The corrosion process leads to the deterioration of equipment material when corrosion material is produced in a variety of methods that increase the environment's resistance to corrosion or have detrimental effects in some applications [6]. An analysis of these strategies will show the advantages and disadvantages of the different deposition methods for layered data. Though there are many methods available, just a select few are considered highly important and effective. These methods include thermal spray, sol-gel (MAO), micro arc oxidation, chemical vapour deposition, physical vapour deposition (PVD), and polymer layer. This strategy is necessary in some situations. Because they have a range of deposits, various materials, secondary, and variable densities and thicknesses, mechanical stability, corrosion resistance, and biocompatibility are important considerations to keep in mind (for particular coating types, biomedical applications, and careful trade-off [7]). As with all forms of protection, material selection is the most important consideration when creating a successful technique [8]. Materials such as metals, ceramics, and polymers can all be used to create a protective layer. However, choosing the right composition for the deposited layer could be challenging given the variety of coating techniques and fabric characteristics. Al, Ti, Hf, Zr, Ni, Co, Pt, MgO, ZrO₂, Al₂O₃, Y₂O₃, BeO, Look, and PTFE are all used in the examples, with emphasis devoted to all the under utilised possibilities. Taking into account the most well-liked solutions is crucial to solving this challenge. Each feedstock material has corrosion or wears resistance, yet they all have different melting points, mechanical properties, and chemical compositions. These models restrict the variety of materials that can be utilized in addition to the variety of powders, sticks, paper, and metal shapes they have in some projects [9]. This evaluation does not cover all preservation techniques, including thermal treatment, mechanical treatment, mechanical/chemical wrapping, and cleaning. The review simply skims through the materials, their surface modification, and the coating method.

TECHNIQUES FOR DEPENDABLE COATING

The coating process provides protection for specific levels or zones of structures that are subjected to risky situations in a variety of industries, including the automotive and aviation sectors as well as microscopic biological devices embedded within the human body [10].

Vapour Deposition Coating

Vapour deposition is the term used to describe any process wherein gaseous components solidify through condensation, reaction, or transformation. The mechanical, electrical, thermal, optical, corrosion, and wear properties of the substrate can all be altered with this method [10]. In order to create composite materials, they are also used in the manufacturing of textiles, films, yarns, and human bodies. The Hoover chamber is where the steam deposition procedure is usually completed. Techniques for vapour deposition can be separated into two categories:

1. Vapour deposition in the physical sense
2. Build-up of chemical vapour

Vapour Deposition in the Physical Sense

This technique holds the coating in place by feeding a stream of neutral or ionised metal particles through the physical vapour deposition (PVD) system, as shown in Figure 1. It is possible to testify about the challenging coating using a range of PVD forms [11]. The mostly used techniques are combined

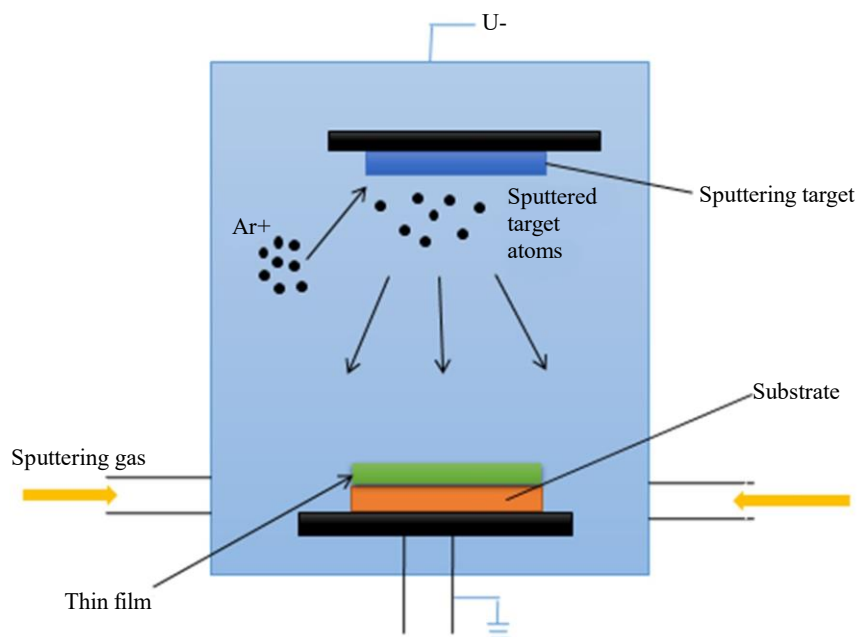


Figure 1. Process of physical vapour deposition.

magnetron and bend forms, magnetron sputtering (or sputter particle plating), and cathodic bend vapour (plasma or circular segment particle plating). The coating process uses plasma and a different evaporation process than the PVD approach. The metal substance (to be deposited) can transition from the solid state to the gas phase, where metal atoms are ionised in various methods (such as magnetron), by heating the evaporation area (for example, in the cathodic arc) or the target sputtering [11]. Using the cathodic circular segment and a magnetron sputtering handle, Ti and Al can be sprayed from cathodes or targets formed of TiAl alloys. Compared to PVD sputtering, the PVD arc evaporation method requires more energy. In order to quickly vaporize a tiny, confined cathode area, arc evaporation entails rapidly passing a high-energy arc through the target metal surface. The plasma is made up of the vaporized heavy ionized metal [12]. In the event of spraying, ions or neutral atoms act to mechanically eject atoms from the target. Nonplanar surfaces cannot be coated by the majority of PVD-based coating methods that don't use more spatially dispersed sources, such as cylindrical magnetron sputtering, or substrate translation or rotation. This is because the vapour diffuses into other materials due to the high vacuum that produces the vapour atoms. Only the area in the stove's line of sight is therefore protected [13]. The cathodic bend approach can suffer from the arrangement of expanding particles. Bead arrangement between circular segments of materials with high melting points, such aluminum, can produce large particles (or expanding beads) in the case of (Ti, Al) N layers. It is also thought that extra atoms from the cathodic arc process quick evaporation make it to the partially ionized substrate surface [14]. These extra-neutral atoms can unite to create larger particles while in flight. There are also leaders who can find a solution to this issue. The increased arc approach and distribution over hot cathodes improve arcing.

Build-up of Chemical Vapour

CVD might be a vapour statement of sorts. The semiconductor industry makes extensive use of the technique of creating a robust, effective, and high-performance layer on any substrate using high vacuum [15]. The CVD method can be used to protect mechanical components against corrosion and wear when they are positioned next to one another. This process involves exposing a mixture of precursors for volatile materials to a wafer-shaped substrate, where the reaction causes a layer of material to be deposited [16]. It is possible that some residues of this reaction remain in the space, despite the vacuum pump's continuous lubricating having removed them. Graphene, polymers, Si combined with O and Ge, carbides, nitrides, oxynitrides, graphene filaments/nanofibers/nantubes, Ti-shaped

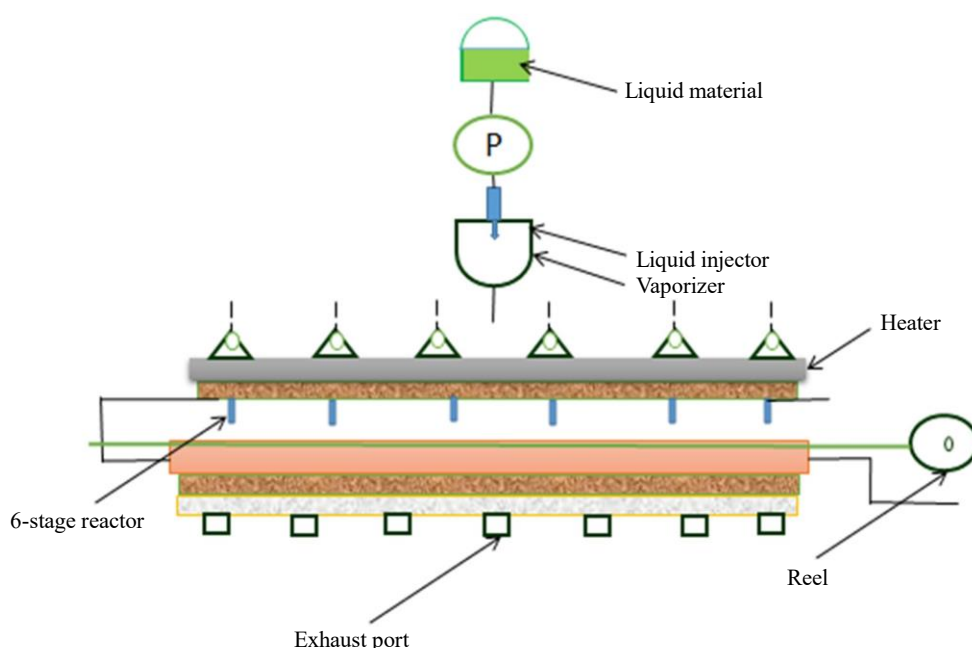


Figure 2. An illustration of the CVD configuration.

carbon, and W are just a handful of the many different materials and material alternatives accessible for CVD technology. These materials can also be used to create a wide range of microstructures, such as shapeless, polycrystalline, and single-crystalline. Furthermore, polymer CVD has proven to be reliable in a range of applications, such as biomedical inserts, circuit sheets, and long-lasting lubricants. Climate weight, cow weight, really tall weight, and tall hoover are the three sorts of CVD forms; the latter two are the most common [17].

There are numerous varieties of CVD shapes, depending on the subsurface temperature, the properties of the fabric, and the kind of plasma employed to vaporize the material. These last categories essentially encompass coordinated fluid implantation CVD, plasma-assisted CVD, microwave plasma-assisted CVD, and light-assisted CVD [18]. There are arguments for and against CVD's superiority over PVD, depending on the application. The substrate has been heated to 900°C, therefore heated materials cannot be used inside the CVD handle. PVD includes a preamble for this information. However, because CVD can cover hot surfaces, waste is not readily apparent. Computer-controlled lasers can be utilised to selectively warm the ranges required to enhance this capability [19]. Figure 2 depicts a schematic of the CVD configuration.

Chemical and Electrochemical Plating

Brenner and Riddell used the phrase “electrolysis metal deposition” in 1946 to describe an autocatalytic method for depositing metals without the aid of an external electrical source. When a reducing agent is added to the bath, an oscillation happens. On the freshly produced catalytically active surface, autocatalytic activity takes place. The creation of new materials for electronic devices, materials resistant to wear and corrosion, materials used in medicine, battery technology, and other vital areas [20]. During galvanic coating, a layer is placed to a cathode, which acts as the electrode (the component to be coated). All metals and alloys are cast in this way, with the exception of titanium and aluminium. Apply the coating with a handheld coating metre in place of a bath. An aqueous electrolytic solution is used as the anode to anodize aluminium and its alloys. The process of regulated autocatalytic deposition of a continuous layer on a catalytic surface through the reaction of a complex substance with a chemical reducing agent is known as electroless plating. With this technique, films can be easily prepared with any kind of low-thickness support and basic equipment. In Figure 3, electroless coatings are depicted.

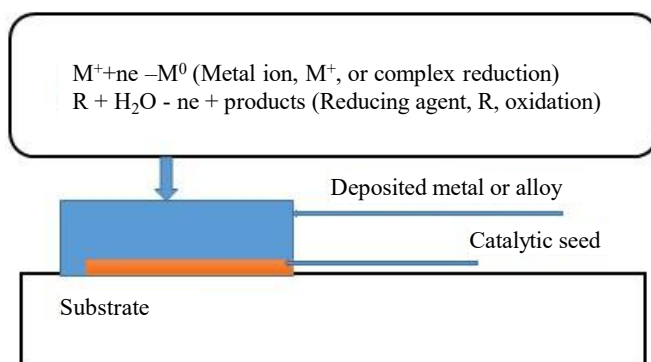


Figure 3. Electro less coatings.

APPLYING SOL-GEL COATING

Sol gel coating is one of the best techniques for biomedical equipment, as Figure 4 illustrates. It is feasible to facilitate the design and execution of experiments while keeping trust in the results by thoroughly researching its applications and methodologies. [21, 22]. Conversely, solgels have the ability to improve corrosion and ion release in existing systems. Because of their liquid permeability, solgels can replace porous and damaged layers rapidly and easily. A precursor to calcium phosphate (CaP) is dissolved in ethanol or distilled water to create sol. The mixture is heated to different temperatures in order to give it the physical strength and consistency required for the gel stage to form. The change from the arranging to the gel stages is referred described as “sol-gel”. When the device or component is ready, it is dropped into the solgel material gradually and gently. To make more or thicker layers of the same object, repeat this procedure. To expedite drying or ready the coated surface for the following step, the coated structure can also be heated.

THERMO SPRAY COATING

The term “warm sputtering” refers to a group of processes that use heat to supply plasma, power, or chemicals to liquefy various electronic materials and spray the resulting liquid fabric over the edges of surfaces to provide a barrier covering. These coatings provide dependable protection against wear and corrosion. In this process, the warm medium which is often created by chemical combustion or plasma release heats the materials to a liquid or semi-finished state. The components are then sprayed with a tall, broad exposure on the substrate. The thicknesses obtained by heated sputtering preparation might

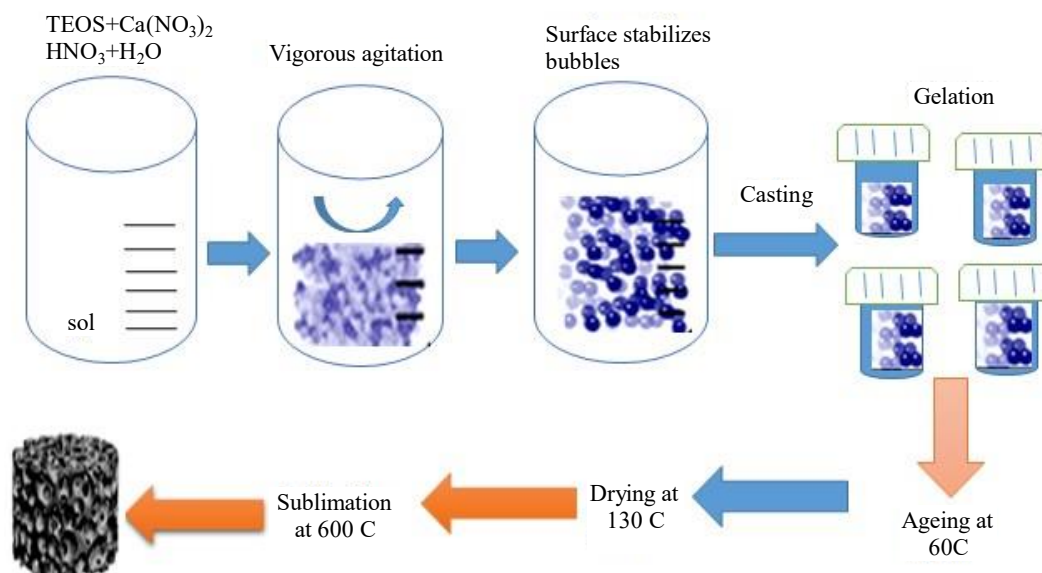


Figure 4. Depicts a sol-gel coating case in schematic form.

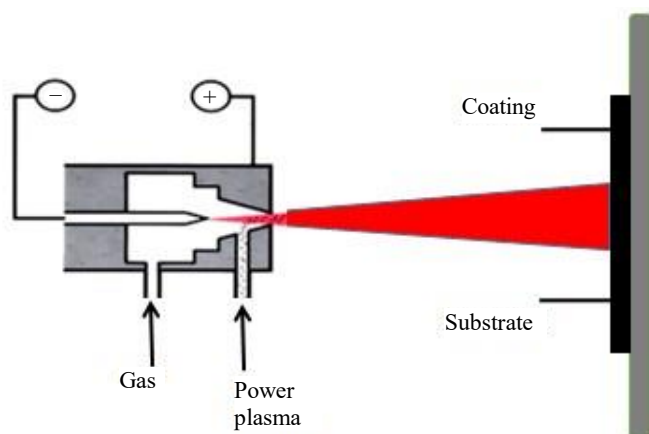


Figure 5. Thermal spray coating.

vary from 20 m to a few millimeters in comparison to galvanic coating preparation, CVD preparation, or PVD preparation [23]. Additionally, strong metals, metal amalgams, ceramics, polymers, composites, and materials that can be utilized as source materials for heated splash coatings are just a few examples of the diverse materials that can be utilized, can be effectively covered with weights that are exceptionally high. Thermal splash coatings fall into several categories with regard to their characteristics and uses. High-speed electric fire (HVOF), high-speed oxygen gas fire (HVOF), blast, hot/cold, electric circular segment shower, and fire [24] are the most prevalent types. Figure 5 illustrates thermal spray coating.

High-velocity Oxy-fuel Coating, or HVOF

The high velocity oxy-fuel coating preparation is schematically depicted in Figure 6. An aqueous or fluid oxygen mixture and a fuel (such as acetylene, propane, methane, hydrogen, or regular petrol) are burned constantly in a combustion chamber that is designed to maintain room temperature and weight. Fly form at 1000 m/s in the combustion chamber, which holds the combustion components in the spout. The nozzle is then used to create a component that melts instantaneously by injecting a covering of burnt powder particles into the hot water jet [25]. When the substance is partially forced to the surface by the electric light, a unique layer that is up to a few millimeters thick forms. The advantage of this technique is that thick layers of premium materials can be used, such as hydroapatite (Zr, oxide, or polymer/primer). The deposition of corrosion and wear-resistant layers is accomplished by using nanocomposite nylon 11/silica and another material. Numerous studies conducted up to this date have shown that HVOF is used in a wide range of corrosive materials and circumstances. The findings of these studies demonstrate the effectiveness of the methods developed with this technology in minimizing substrate deterioration.

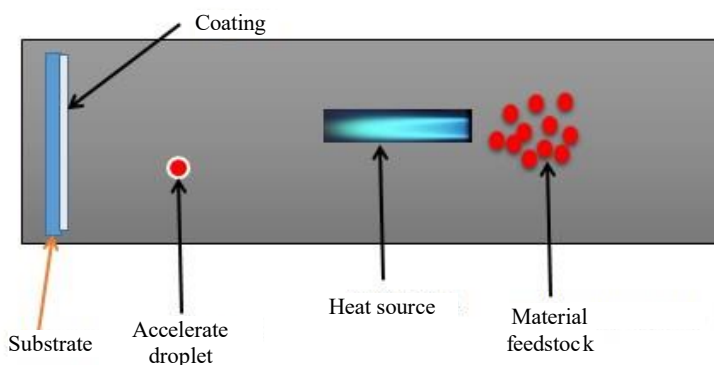


Figure 6. A high-velocity oxyfuel (HVOF) coating framework is constructed schematically.

Plasma Spray Coatings

Figure 7 displays the profile of the plasma fly layer. The process can be done in an air or vacuum environment. With temperatures as high as 10,000K, the hot coordinate current/induction plasma produced by the plasma weapon effectively dissolves tough metals, ceramics, and plastics. Cross-breed plasma, oil, or water could be used as materials for plasma stabilisation. The object needs to be in hot plasma in order to lessen the charge. Liquid beads are maintained firmly on the substrate relative to the coating because of the high plasma speed at the focalized spouts tip. The usage of several fundamental material types, such as powders, slurries, suspensions, and fluids, is encouraged by the simplicity of this method [26]. Notable advancements in erosion and wear resistance have resulted from numerous studies on various materials, including chromium oxide and NiCr amalgams [27, 28]. Look, a type of plasma showered polymer coating, has been used as cover layers, work and paper discharge coatings, harm-free coatings, dampness obstructions, and erosion protection for plastic moulds.

Vacuum plasma implantation, on the other hand, is a common technique for replacing the surface of substrates with materials that are resistant to environmental influences. The most common application of vacuum plasma showering is surface alignment of construction materials, like as metals, filaments, and elastic [29].

Cold Spray Coating

This procedure is built on a mixture of elements and outcomes. It does not require thermal applications, unlike HVOF and plasma. The size of the coated material, the goal temperature, the material, and the critical velocity all affect the entire cold spraying process [30]. To obtain the necessary kinetic energy, the particle material is submerged in high pressure liquids (helium and nitrogen). This force deforms the material and adheres it to the substrate following the interaction between the material and the substrate.

Rapid application of the selected material is achieved by pressing the material into place. Numerous metals, alloys, composites, polymers, and ceramics are among the most commonly utilised powder materials [31]. In addition, it has been noted in the literature that some hard materials, such as tungsten and titanium, are coated, despite the fact that soft metals like aluminium and copper are among the most investigated materials [32]. In certain investigations, the environment's temperature was raised to boost process effectiveness [33]. The operating range is somewhat limited, however the process is simple and affordable when compared to other thermal spraying techniques. The cold spray coating process is depicted in Figure 8.

Warm Spray Coating

The warm splash method is schematically shown in Figure 9. When compared to cold splashing, low operating temperature reduces the sufficiency and consistency of the warm splash handle. In any event, high temperatures dissolve unrefined materials and produce unused reactions that can overheat substrates

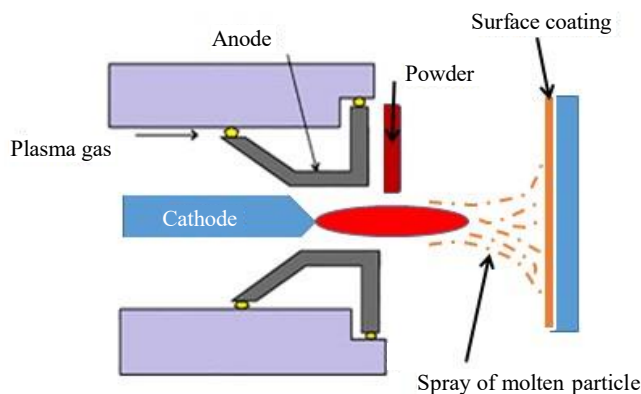


Figure 7. Components of the plasma spray coating system diagram.

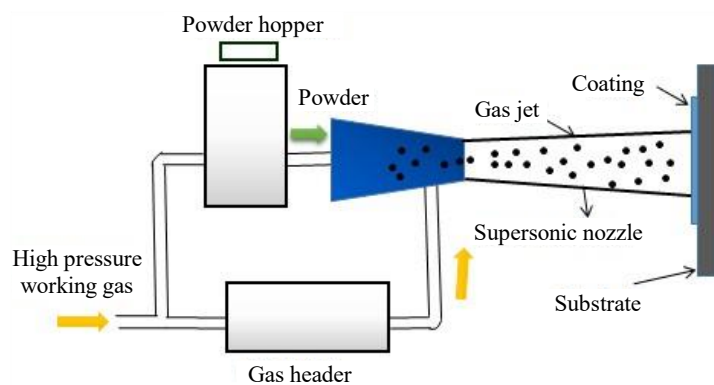


Figure 8. Depicts the cold spray coating procedure schematically.

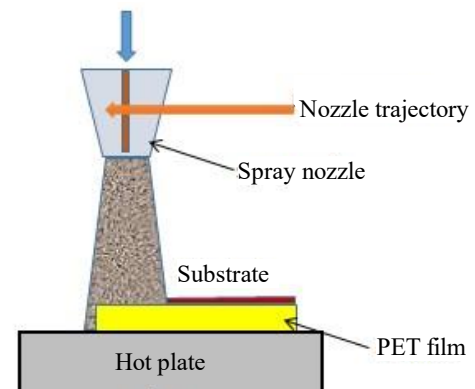


Figure 9. Warm spray coating.

and objects, which can lead to oxidation or other alterations in the materials. Warm shower paint is a contemporary invention that was developed to solve this problem. The temperature of the combustion chamber can be lowered by adjusting the HVOF layer by including nitrogen gas into the fluid mixture. This technique offers an extraordinarily efficient coating preparation that lies midway between cold showering and HVOF coating [34]. However, due to the proximity of oxygen at high temperatures and rapid stream, the approaching layer has more debasements than other layers, as described in the literature.

Arc Wire Spray Coatings

An electric arc can be used to melt wires using an arc spray technique. Other names for it include thermal arc spray and twin-wire arc spray. There are “push” and “push/pull” arc spray systems available, and they are usually thought to be easy to operate and automate. Compared to a “push/pull” gun, a “push” system is lighter and more straightforward. It is typically utilised in engineering applications where hard engineering wires are employed and when the distance between the machine and the gun is shorter (5 metres). “Push/pull” systems are commonly employed in anti-corrosion tasks using soft wires, such as zinc and aluminium when a greater distance between the gun and the machine is required [35–40]. The systems push or pull two wires to the spray gun. When the wires are forced together and an electric arc is formed, the wire melts. The molten metal is driven through a nozzle and then atomises with compressed air before being sprayed onto the work item. These wires, for instance, are interchangeable and can be used as one-wire zinc or one-wire aluminium. The current rating of the system causes an increase in the spray rate. Figure 10 show the setup and coating techniques of arc wire spray coatings [41–44].

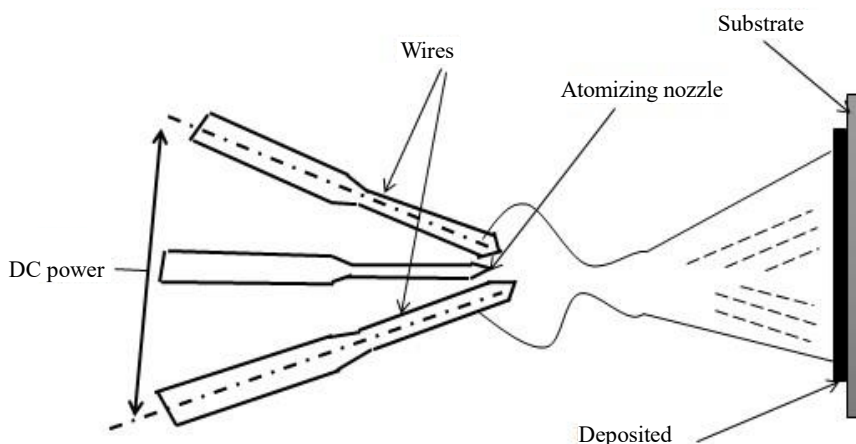


Figure 10. Diagram showing the setup and component of operation for a circular segment wire shower coating.

Arc spray is a very versatile thermal spray technique that offers a cost-effective solution for applying metallic coatings in various applications. Applying corrosion protection coatings to steel fabrication is an easy operation. Similarly, engineered coatings can be used to spray objects to modify or rebuild their surface qualities [65–67]. It is quite easy to switch between engineering and anti-corrosion wires. It is possible to spray coatings made of zinc, aluminium, steel, copper, bronze, and other materials for surface modification, engineering reclamation, corrosion protection, and decorating [46–50]. Arc spraying usually has more significant initial expenditures than flame spraying, but it usually has lower ongoing expenses (Tables 1 and 2).

Flow Diagram of surface coating methods

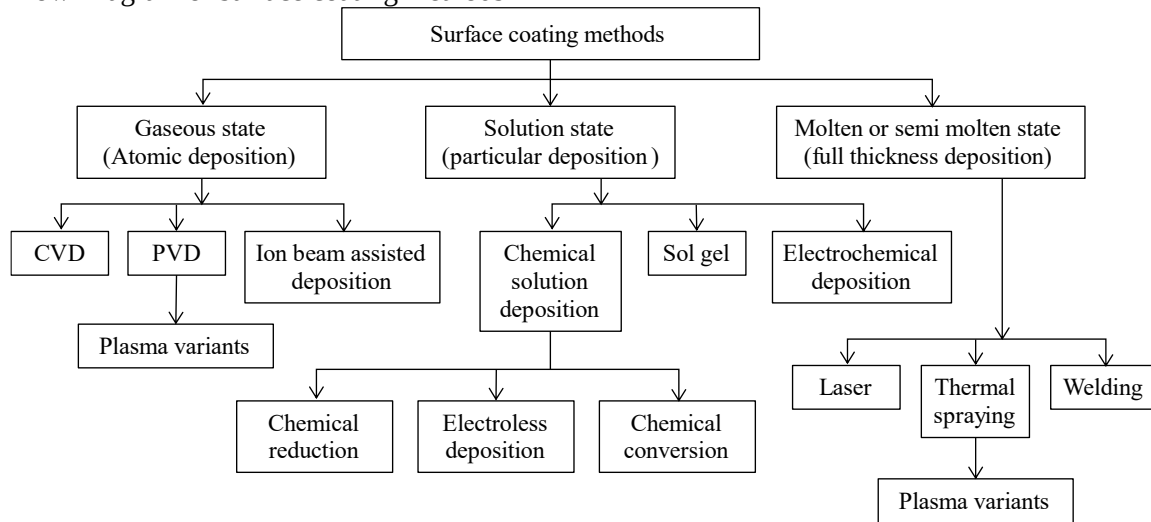


Table 1. Rundown of coating forms and their particular highlight

Precipitation process	Origin	Material for feed stocks	Substrate material	Coating thickness (µm)	Refs.
PVD	Physical	PVDF, TiN, TiC _x O _y , ZrC _x O _y , PE,	Glass, Si, potassium, AISI M2 STEEL, SS	1.2–6.3, 5, 0.2, 0.2, 0.1, 0.1	36
CVD	Chemical	Niobium oxide (Nb ₂ O ₅), W-TiN-WSi ₂ -Ta ₂ O ₅ -CuSiO ₂ , polycrystalline Si- Si ₃ N ₄ -SiO ₂ , PTFE, Ni ₃ Ti	Glass, Si, Si, Kleenex, Ni-Co-Fe	0.05–0.2 and 0.2–0.6	37
MAO	Electrochemical	PCL duplex, hydroxyapatite (HA)/TiO ₂ , and HA-HA/ZrO ₂	Ti-6Al-4V, Mg and NiT	10–20, 2–4, 7	37, 38
ELD	Electrochemical	Zn-Ni-AlO ₃ , Ni-Co-Al ₂ O ₃ , Ni-Co-Si, PPY	Cu, mild steel, carbon steel and steel	10–70, 50–200	39
Sol-gel	Physical	Methyltriethylortho silicate, or TEOS-Polycarbonate, PDMS, HA, and MTEOS	Stainless steel, Si, NiTi	0.01–1, 1–4	40
HVOF	Thermal	HA, CoNiCrAlY, WC, Al ₂ O ₃ , zirconia (YSZ), Metco 447	Inconel 738 metal, Ti-6Al-4V and AISI 4340 SS	70–100	41
Plasma spray	Thermal	TiC-NiCrBSi, Alumina/Titania 87/13, Nicrome 80/20, Hastalloy G30	AISI 4140 steel, stainless steel	0.5–1	42
Cold spray	Physical	HA, AA7075, combined Ni/Al/MoO ₃ , Ni-clad Al, and Ni/Al	Al 6061-T6, Ti-6Al-4V, Al 6061	100–1000, 40–300,	43, 44
Warm spray	Physical	WC-Co, Ti, Zr-Cu12.3Ni7.6-Al _{3.5} , Ti	Carbon steel, steel, steel, and 316L SS	400–1000	45, 46
Arc wire spray	Thermal	TiC-Fe, MoS ₂ -Ti/Al	Steel carbon, SUS 304	1000	47

Table 2. Preferences and drawbacks of dependable coating forms.

Deposition process	Advantages	Disadvantages	Refs.
PVD	Lean film evidence that is functional and customizable, with mechanical, erosion, and aesthetically pleasing highlights as well as erosion resistance	In polymer deposition applications, high speed is necessary, wear impacts corrosion protection, and control deterioration is challenging.	48
CVD	Operation at low and ambient pressure, deposition of diverse materials with varying microstates, and protection against corrosion and wear	Heat-resistant equipment, lots of electricity, and little coating waste are all desirable	48
MAO	Porous structure for biological applications, high hardness and resilience to corrosion, and a range of porosity scales across the thickness.	mostly applicable to valve metals	49
ELD	Applications for wear, decoration, high-temperature use, and low corrosion	It can be used on conductive surfaces.	50,51
Sol-gel	Cost-effectiveness, biomedical uses, resistance to ions and corrosion, thick, multilayered coatings, strong adhesion, and This content offers each of these advantages. due to the lack of conductive substrate restrictions, composition freedom, and complex geometries	Controlling coating thickness, having a long cycle time, and the potential for coating failure during heat treatment on objects with several layers of coatings	52
HVOF	High substrate adhesion, corrosion and wear resistance, compatibility with non-conductive surfaces, and high coating layer density	needs a tight size distribution, a heat source, a large number of process variables, and a small range of particle sizes (5 to 60 m).	53
Cold spray	This is a cheap and easy process in comparison to other thermal spray methods.	Low working temperature range; mostly used for soft and hard metal surfaces; poor durability and efficiency because of low temperatures; inefficient under extremely demanding circumstances	54
Warm spray	Ideal for heat-sensitive materials or those susceptible to oxidation at elevated temperatures.	Extremely harsh environments with impurity problems	55, 56
Spraying arc wire	Surface coatings inside engines that withstand corrosion and wear	The coating layer can only be made of wires and conductive materials.	57, 58

COATINGS VARIOUS APPLICATION AREAS IN VARIOUS INDUSTRIES

Automobile

In the modern world, automobiles are the primary means of transportation. Automobile safety advocates believe that designing a corrosion-resistant car body (which increases durability) and a clean windscreen (which ensures the driver can see properly) are becoming more and more important [59, 60]. For maximum safety, reduced maintenance costs, and increased vehicle longevity, the surfaces of the two aforementioned sections should have multifunctional super hydrophobic coatings[51-58].

Wind Breakers

Super hydrophilic coatings have a spreading effect that produces a continuous, scatter-free water film, which eliminates fogging entirely. These high surface energy molecules quickly become contaminated, though. The use of super hydrophobic coatings on automotive wind shields that are self-cleaning and anti-fogging has grown in popularity [60]. The anti-fogging capabilities of super hydrophobic coatings are believed to be caused by the rapid evaporation of small fog droplets that form on super hydrophobic surfaces. Additionally, fog droplets that are leaving super hydrophobic surfaces at an angle move more quickly when rolling, according to researchers. The most important consideration for any coating applied over wind shields is transparency. There is often conflict between surface roughness, optical transmittance, and super hydrophobicity [61]. As surface roughness increases, transparency decreases and hydrophobicity grows. This is because the refractive index of the material surfaces, which is frequently influenced by the huge diameters of the roughness features, and

feature size both affect light scattering, which in turn impacts light transmittance. Super hydrophobicity requires a combination of micro and nanostructure, which would increase the surface's capacity for self-cleaning but result in an opaque finish. It has been suggested that super hydrophobic coatings can be made without affecting coating transparency by utilizing techniques that combine nanoparticles and low surface energy components. Surface roughening materials like nanosilica (SiO_2), nanotitanium dioxide (TiO_2), and nanocalcium carbonate (CaCO_3) are frequently used.

It is said that super hydrophobic coatings are not just vapor-repellent but also water resistant. Temperature variations cause the phenomenon of water vapour condensation on surfaces; below the dew point, super hydrophobic coatings stop repelling water. In order to prevent windscreens from fogging, further study needs to be done on the use of super hydrophobic materials.

Car Body

Most steel and other lightweight materials, such as alloys made of aluminium, magnesium, and other metals, are used in practical applications for car bodies to reduce the water contact area of super hydrophobic coatings, minimise corrosion of metal alloy surfaces, and lower contaminant adhesion strengths to super hydrophobic surfaces. This results in a slower rate of corrosion and an enhanced ability of the car's body to clean itself. Super hydrophobic material coatings, therefore, are excellent choices for enhancing the anti-corrosion and self-cleaning properties of substrates on metal surfaces. Nearly 90% of the materials used in the construction of automobiles are made of steel due to its exceptional physical and mechanical qualities, which include its high hardness, outstanding castability, high stiffness/weight ratios, and great damping capabilities. Conversely, steel corrodes quickly because of its high electrochemical and chemical activity [61]. Steel substrates now have significantly better corrosion resistance, particularly when it comes to ultra hydrophobic coatings.

Marine

Economic growth, high energy consumption, and corrosion issues undoubtedly brought on by a variety of maritime activities, particularly in the harsh marine environment, have had a considerable impact on maritime transportation and operations. To achieve the highest standards in real-world marine applications, a number of academics have focused on improving the performance of boats and marine infrastructure. Here, super hydrophobic coatings are a crucial technological advancement that can improve the corrosion resistance of boats and marine infrastructure as well as the drag reduction of seafaring goods [62].

Marine Vessels

Reduced drag on surface and submerged ships can boost sailing speeds and save fuel use greatly at sea [62]. Maritime vessels such as cargo ships, service ships, navy warships, submarines, and more can use extremely hydrophobic coatings. With their exceptional water-repellency and low water adhesion force, these coatings offer significant advantages in terms of easy manufacture and low energy usage. This technology can also lower drag and improve operational performance.

It is important to note that super hydrophobic coatings are not very effective at reducing vessel drag due to their low mechanical endurance, particularly with regard to abrasion resistance. Consequently, a number of efforts have been undertaken to enhance super hydrophobic coatings' mechanical toughness and drag-reduction effectiveness.

Aircraft

Ice at the airfoil and empennage is responsible for most aero plane mishaps. The main reasons why freezing occurs during a flight include often super cooled liquid water in the clouds, which stays liquid below zero and then abruptly turns into ice, as well as the presence of small ice particles. An aerodynamic stall or even a serious safety issue may occur from ice accumulation and aggregation on an aircraft. Moreover, it ruins the aircraft's equipment and makes flying more challenging [63].

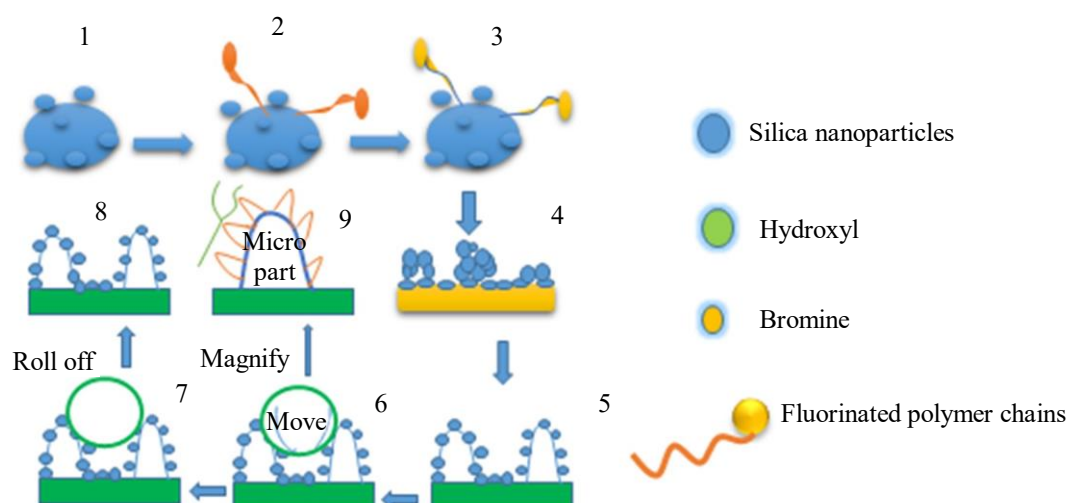


Figure 11. Schematic of the manufacture and application of super hydrophobic anti-icing surface.

The energy-intensive techniques used in current aircraft de-icing and anti-icing technologies such as thermal, mechanical, or chemical treatment are neither economically viable nor environmentally sustainable. The aircraft systems' increased weight and complexity particularly the labour and time-intensive de-icing process will result in increased fuel consumption. They also discharge pollutants into the sky. It is possible to lessen the amount of ice adhesion and minimise ice development on aircraft surfaces by using anti-icing and ice-phobic coatings. Condensed water may roll off substrates prior to freezing as a result of outside factors like gravity, wind, centrifugal forces, etc. This prevents the development of ice by extending the freezing period and decreasing the freezing temperature of super-cooled liquid water. Super hydrophobic coatings were made using several production techniques to increase their ice-phobicity and anti-icing properties. The feasibility of developing anti-icing and ice-phobic coatings using both conventional techniques like spin-coating and sol-gel processes and cutting-edge techniques like atom transfer radical polymerization (ATRP) was covered in this paper. The application and surface preparation of super hydrophobic anti-icing was demonstrated in Figure 11.

Sunlight Power

Every year, 10,000 times more solar energy (5×10^{24} J) than the world's actual yearly energy consumption reaches the earth's surface. Because of this year-round abundance of sunlight and technological advancements in light energy capture, solar energy has come to be acknowledged as the most important renewable energy source [63]. Photoelectric and photo thermal conversion are two more ways to use solar energy. In these two procedures, solar flat-plate collectors and solar photovoltaic (PV) panels are frequently utilised. In practical applications, the accumulation of dust and pollutants on the surfaces of these devices adversely impacts both electric and thermal consumption, severely reducing both the performance of the solar thermal system and the PV output efficiency. Thus, it would be perfect to emphasise solar energy transfer and offer extremely hydrophobic coatings that are also self-cleaning.

Medical Application

Numerous techniques have been developed to generate medical-grade zirconium dioxide, considering the properties required for different biological applications. Improved results that might be used in biomedical domains were found by analyzing the sol gel synthesis method used to produce medical-grade zirconium dioxide. Figure 12 shown developing zirconium dioxide modification approaches for medical applications [64–67].

They discovered that whirling a solution of propanol, ammonia, and water for five minutes produced zirconium dioxide nanoparticles. After that, add the zirconium propoxide and stir for one hour. After that, the resulting sol is dried in an oven and heated to 70°C. Following that, the zirconium dioxide

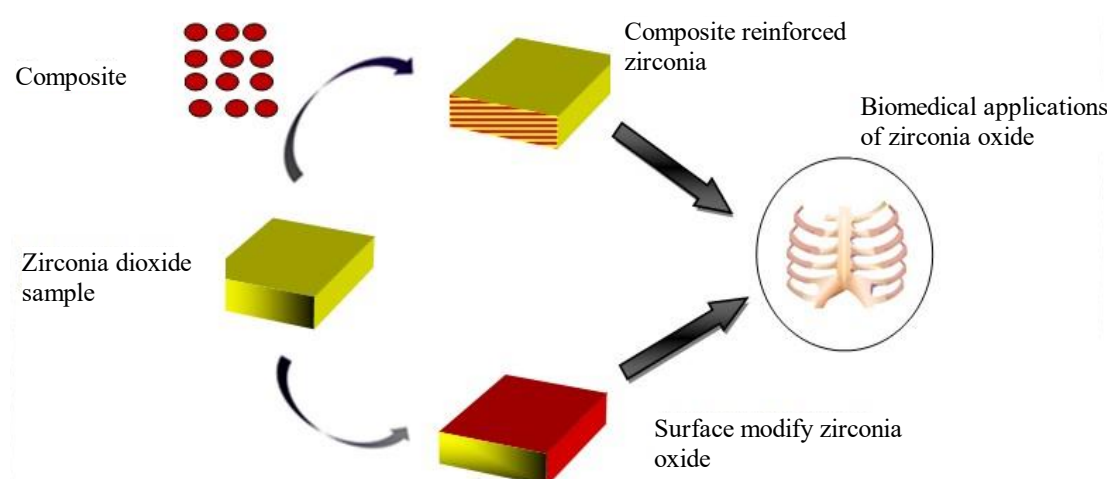


Figure 12. shows a schematic for developing zirconium dioxide modification approaches for medical applications.

powder is dried and heated to a maximum temperature of 500°C during the course of two hours of calcination. The synthesis procedure fixes the molar ratio of propanol, water, and zirconium propoxide at 20:8:1 to provide the best processing results. Equations (1), (2), and (3) show the chemistry needed to produce zirconium dioxide by the sol gel method. Partially hydrated alkoxide



Alkoxy or hydroxyl group polymer condensation



CONCLUSION

There are numerous methodological angles presented in this review. This article aims to promote understanding of the usage of various wear-reduction procedures. If the process is increased, the membrane's sealing will also be improved, and it will have less porosity and better corrosion resistance. Aerospace, ground turbines, car production, ceramics and glass, printing, pulp and paper, metallurgy, medical, nuclear power, cement plant spray, and waste treatment are just a few of the industries that frequently use anticorrosion coatings. Physical and chemical vapour deposition (PVD/CVD), micro arc oxidation (MAO), electrodeposition (e.g., galvanic coating), electrophoretic deposition (EPD), solgel, and various thermal sputtering processes (e.g., HVOF, plasma, cold, thermal, and arc sputtering) are among the most efficient thermal sputtering techniques. Since the teaching process employs a range of strategies to position certain items on the website, selecting the appropriate materials is crucial to achieving a good process. Heat can be used in some procedures to transform food into liquids and semi-solids in the form of clumps, droplets, and particles.

In conclusion, the use of high temperature and high speed plasma jets improves the efficiency of thermal operations, such as different forms of thermal spraying. This method enables the processing of the raw material at low temperatures and fast speeds while removing the detrimental impacts of the high melting points of ceramics and super alloys. These conditions give rise to layers that could be hundreds of microns thick. However, depending on the process, the layer microstructure may also include porosity and oxide and carbide inclusions. The only applications for deposition coatings based on evaporation technology are the coating of equipment and the protection of sliding mechanical parts. These thin films have good corrosion/wear resistance. Micro arc oxidation, a high conversion of iodization, is frequently employed in biomaterials for applications like bone implants and biomedical equipment. Al, Ti, Zr, Hf, V, and Nb are common substrate use metals for valves. The coating produced

by MAO during bone formation provides strong substrate/layer adhesion and porosity, which is essential for biomaterial coatings. The porous microstructure also improves corrosion resistance and facilitates the use of engineering models to estimate plant lifespan, depending on the rate and duration of plant degradation. Since an aqueous solution acts as the process' carrier, the complexity of the geometry has no bearing on the process' quality. Another tested substance, solgel, offers many nutritional benefits. A sealant called solgel deposits is used to increase the corrosion resistance of porous substrates and coatings. The solgel method is slow and labor-intensive to fabricate, even with its diversity and layering powers. The employment of electrochemical processes, which depend on the charge difference between the anode and cathode of a chemical cell, is another method of purifying water.

REFERENCES

1. G.Frommeyer. G. Wassermann, "Anomalous properties of in situ-produced silver copper composite wires I. Electrical conductivity." *Physica status solidi(a)* 27.1 (1975) 99-105. <https://doi.org/10.1002/pssa.2210270112>
2. H Ibrahim, AR Jahadabkar, A Dehghan, NS Moghaddam, A Amerinatanzi, M Elahinia, "In vitro corrosion assessment of additively manufactured porous NiTi structures for bone fixation applications." *Metals* 8.3 (2018) 164. <https://doi.org/10.3390/met8030164>
3. SaerehMirzababaei, Peter Filip, "Impact of humidity on wear of automotive friction materials." *Wear* 376 (2017) 717-726. <https://doi.org/10.1016/j.wear.2017.02.020>
4. B.Bhushan, B K Gupta, *Handbook of Tribology: Materials, coatings, and surface treatments*. United States N. p., 1991-12-31 Web.
5. Amir Dehghanghadikolaei, BehrouzMohammadian, NavidNamdari, BehzadFotovatiet, "Abrasive machining techniques for biomedical device applications." *J.Mater. Sci* 5.1 (2018) 1-11. <https://DOI: 10.19080/JOJMS.2018.04.555653>.
6. C.D. Klaassen, D. Curtis, Mary O. Amdur, eds. *Casarett and Doull's toxicology: the basic science of poisons*. Vol. 1236. New York: McGraw-Hill, 2013.
7. M.R.Thakare, JA Wharton, RJK Wood, C Menger, "Exposure effects of alkaline drilling fluid on the microscale abrasion–corrosion of WC-based hard metals." *Wear* 263.1-6 (2007) 125-136. <https://doi.org/10.1016/j.wear.2006.12.047>
8. Jeanine T. DeMasi-Marcin, Dinesh K. Gupta, "Protective coatings in the gas turbine engine." *Surface and Coatings Technology* 68 (1994) 1-9. [https://doi.org/10.1016/0257-8972\(94\)90129-5](https://doi.org/10.1016/0257-8972(94)90129-5)
9. RK Annavarapu, S Kim, M Wang, AJ Hart, H Sojoudi, "Explaining evaporation-triggered wetting transition using local force balance model and contact line-fraction." *Scientific reports* 9.1 (2019) 405. <https://doi.org/10.1038/s41598-018-37093-6>
10. Nan Gao,Yuying Yan., "Modeling superhydrophobic contact angles and wetting transition." *Journal of Bionic Engineering* 6.4 (2009) 335-340. [https://doi.org/10.1016/S1672-6529\(08\)60135-3](https://doi.org/10.1016/S1672-6529(08)60135-3)
11. Naveen Kumar, Vikas Kumar Choubey, "Comparative evaluation of oxidation resistance of detonation gun-sprayed Al₂O₃–40% TiO₂ coating on nickel-based super alloys at 800° C and 900° C." *High Temperature Corrosion of Materials* 99.5 (2023) 359-373. <https://doi.org/10.1007/s11085-023-10157-3>
12. Naveen Kumar, Vikas Kumar Choubey, "Effect of WC-Co and 86WC-10Co-4Cr coatings on type-II hot corrosion behaviour& microstructure characteristics at 650 degree celsius." *Surface and Coatings Technology* 469 (2023) 129812. <https://doi.org/10.1016/j.surfcoat.2023.129812>
13. Karen K Gleason, "Overview of chemically vapor deposited (CVD) polymers." *CVD Polymers: Fabrication of Organic Surfaces and Devices* (2015) 1-11. <https://doi.org/10.1002/9783527690275.ch1>
14. Naveen Kumar, V.K Choubey, "Recent trends in coating processes on various AISI steel substrates: A review". *Journal of Materials Science* 59 (2023): 1-28.
15. NaveenKumar, Vikas Kumar Choubey, "Experimental investigation on hot corrosion, oxidation and microstructure of WC based cermet HVOF coating." *High Temperature Corrosion of Materials* (2023) 1-20. <https://doi.org/10.1007/s11085-023-10179-x>

16. Yiming Li, David Mann, Marco Rolandi, Woong Kim, Ant Ural, Steven Hung, Ali Javey, Jien Cao, Dunwei Wang, Erhan Yenilmez, Qian Wang, James F. Gibbons, Yoshio Nishi, Hongjie Dai, "Preferential growth of semiconducting single-walled carbon nanotubes by a plasma enhanced CVD method." *Nano letters* 4.2 (2004) 317–321. <https://doi.org/10.1021/nl035097c>
17. Behzad Fotovvati, Amir Dehghanghadikolaei, and Navid Namdari, "Laser-Assisted coating techniques and surface modifications: A short review." *Particulate Science and Technology* 39.6 (2021) 738-747. <https://doi.org/10.1080/02726351.2020.1812778>
18. Behzad Fotovvati, Steven F. Wayne, Gladius Lewis, Ebrahim, "A review on melt-pool characteristics in laser welding of metals." *Advances in Materials Science and Engineering* 2018 (2018). <https://doi.org/10.1155/2018/4920718>
19. Amir Dehghanghadikolaei, Jamal Ansary, Reza Ghoreishi, "Sol-gel process applications: A mini-review." *Proc. Nat. Res. Soc* 2.1 (2018) 02008-02029. <https://doi.org/10.11605/j.pnrs.201802008>
20. Lech. Pawlowski, *The science and engineering of thermal spray coatings*. John Wiley & Sons, West Sussex, England, 2008, p.85.
21. R. Joseph Davis, ed. *Handbook of thermal spray technology*. ASM international, 2004.
22. A Rabiei, DR Mumm, JW Hutchinson, R Schweinfest, M Ruhle, AG Evans, "Microstructure, deformation and cracking characteristics of thermal spray ferrous coatings." *Materials Science and Engineering: A* 269.1-2 (1999) 152-165. [https://doi.org/10.1016/S0921-5093\(99\)00132-X](https://doi.org/10.1016/S0921-5093(99)00132-X)
23. J Karthikeyan, CC Berndt, J Tikkanen, S Reddy, H Herman, "Plasma spray synthesis of nanomaterial powders and deposits." *Materials Science and Engineering: A* 238.2 (1997) 275-286. [https://doi.org/10.1016/S0921-5093\(96\)10568-2](https://doi.org/10.1016/S0921-5093(96)10568-2)
24. Naveen Kumar, Vikas Kumar Choubey, "Investigation of microstructure and Isothermal oxidation resistance of cermet HVOF coated on AISI316L at 900° C." *Results in Surfaces and Interfaces* 14 (2024) 100173. <https://doi.org/10.1016/j.rsurfi.2023.100173>
25. N. K Mishra, Naveen Kumar, S. B. Mishra, "Hot Corrosion Behaviour of Detonation Gun Sprayed Al₂O₃-40TiO₂ Coating on Nickel Based Superalloys at 900° C." *Indian Journal of Materials Science* 2014 (2014). <https://doi.org/10.1155/2014/453607>
26. E. Petrovicova, L. S. Schadler, "Thermal spraying of polymers." *International materials review* 47.4 (2002) 169-190. <https://doi.org/10.1179/095066002225006566>
27. Srinivasa Kartik Nemani, Rama Kishore Annavarapu, Behrouz Mohammadian, Asif Raiyan, Jamie Heil, Md. Ashraful Haque, Ahmed Abdelaal, Hossein Sojoudi, "Surface modification of polymers: methods and applications." *Advanced Materials Interfaces* 5.24 (2018) 1801247. <https://doi.org/10.1002/admi.201801247>
28. LC Betancourt-Dougherty, RW Smith, "Effects of load and sliding speed on the wear behavior of plasma sprayed TiCNiCrBSi coatings." *Wear* 217.1 (1998) 147-154. [https://doi.org/10.1016/S0043-1648\(97\)00212-3](https://doi.org/10.1016/S0043-1648(97)00212-3)
29. Nitin P. Padture, Maurice Gell, Eric H. Jordan, "Thermal barrier coatings for gas-turbine engine applications." *Science* 296.5566 (2002) 280-284. <https://doi.org/10.1126/science.1068609>
30. Victor K Champagne, "The cold materials spray deposition process." *Woodhead Publishing Series in Metals and Surface Engineering* vol. 5 (2007) Page i. <https://doi.org/10.1533/9781845693787>
31. CJ Li, HT Wang, Q Zhang, GJ Yang, WY Li, HL Liao, "Influence of spray materials and their surface oxidation on the critical velocity in cold spraying." *Journal of Thermal Spray Technology* 19 (2010) 95-101. <https://doi.org/10.1007/s11666-009-9427-x>
32. WY Li, H Liao, CJ Li, HS Bang, C Coddet, "Numerical simulation of deformation behavior of Al particles impacting on Al substrate and effect of surface oxide films on interfacial bonding in cold spraying." *Applied Surface Science* 253.11 (2007) 5084-509. <https://doi.org/10.1016/j.apsusc.2006.11.020>
33. Y. C Tsui, C. Doyle, T. W. Clyne, "Plasma sprayed hydroxyapatite coatings on titanium substrates Part 1: Mechanical properties and residual stress levels." *Biomaterials* 19.22 (1998) 2015-2029. [https://doi.org/10.1016/S0142-9612\(98\)00103-3](https://doi.org/10.1016/S0142-9612(98)00103-3)
34. T Schmidt, H Assadi, F Gartner, H Richter, T Stoltenhoff, H Kreye, Thomas Klassen, "From particle acceleration to impact and bonding in cold spraying." *Journal of thermal spray technology* 18 (2009) 794-808. <https://doi.org/10.1007/s11666-009-9357-7>

35. J Kawakita, H Katanoda, M Watanabe, K Yokoyama, S Kuroda, "Warm Spraying: An improved spray process to deposit novel coatings." *Surface and Coatings Technology* 202.18 (2008) 4369-4373. <https://doi.org/10.1016/j.surfcoat.2008.04.011>
36. I.Gedzevicius,AlgirdasVaclovasValiulis, "Analysis of wire arc spraying process variables on coatings properties." *Journal of Materials Processing Technology* 175.1-3 (2006) 206-211. <https://doi.org/10.1016/j.jmatprotec.2005.04.019>
37. Jin Kawakita, N Maruyama, S Kuroda, S Hiromoto, A Yamamoto, "Fabrication and mechanical properties of composite structure by warm spraying of Zr-base metallic glass." *Materials Transactions* 49.2 (2008) 317-323. <https://doi.org/10.2320/matertrans.T-MRA2007882>
38. Y. C Tsui, C. Doyle, T. W. Clyne, "Plasma sprayed hydroxyapatite coatings on titanium substrates Part 2: optimisation of coating." *Biomaterials* 19.22(1998) 2031-2043. [https://doi.org/10.1016/S0142-9612\(98\)00104-5](https://doi.org/10.1016/S0142-9612(98)00104-5)
39. KeeHyun Kim, M Watanabe, J Kawakita, S Kuroda"Grain refinement in a single titanium powder particle impacted at high velocity." *ScriptaMaterialia* 59.7 (2008) 768-771. <https://doi.org/10.1016/j.scriptamat.2008.06.020>
40. PornthepChivavibul, Makoto Watanabe, Seiji Kuroda, Jin Kawakita, Masayuki Komatsu, Kazuto Sato, Junya Kitamura, "Development of WC-Co coatings deposited by warm spray process." *Journal of Thermal Spray Technology* 17 (2008) 750-756. <https://doi.org/10.1007/s11666-008-9271-4>
41. P.Skarvelis, G. D. Papadimitriou, "Plasma transferred arc composite coatings with self lubricating properties, based on Fe and Ti sulfides: Microstructure and tribological behavior." *Surface and Coatings Technology* 203.10-11 (2009) 1384-1394. <https://doi.org/10.1016/j.surfcoat.2008.11.010>
42. Takayuki Watanabe, Tadayuki Sato, AtsushiNezu, "Electrode phenomena investigation of wire arc spraying for preparation of Ti-Al intermetallic compounds." *Thin Solid Films* 407.1-2 (2002) 98-103. [https://doi.org/10.1016/S0040-6090\(02\)00019-6](https://doi.org/10.1016/S0040-6090(02)00019-6)
43. HosseinSojoudi, Sanha Kim, Hangbo Zhao, Rama Kishore Annavarapu, DhanushkodiMariappan, A John Hart,Gareth H. McKinley, Karen K. Gleason, "Stable wettability control of nanoporous microstructures by iCVD coating of carbon nanotubes." *ACS applied materials & interfaces* 9.49 (2017) 43287-43299. <https://doi.org/10.1021/acsami.7b13713>
44. Nemani, SrinivasaKartik, HosseinSojoudi, "Barrier performance of CVD graphene films using a facile P₃HT thin film optical transmission test." *Journal of Nanomaterials* 2018 (2018). <https://doi.org/10.1155/2018/9681432>
45. Amin Joukar, Jwalant Mehta, David Marks, Vijay K. Goel, "Lumbar-sacral destruction fixation biomechanics: a finite element study." *The Spine Journal* 17.11 (2017) S335. <https://doi.org/10.1016/j.spinee.2017.10.062>
46. AtiehMoridi, SM Hassani-Gangaraj, M Guagliano, M Dao, "Cold spray coating: review of material systems and future perspectives." *Surface Engineering* 30.6 (2014) 369-395. <https://doi.org/10.1179/1743294414Y.0000000270>
47. AlexandreSabard, H. L. de Villiers Lovelock, Tanvir Hussain, "Microstructural evolution in solution heat treatment of gas-atomized Al alloy (7075) powder for cold spray." *Journal of Thermal Spray Technology* 27 (2018) 145-158. <https://doi.org/10.1007/s11666-017-0662-2>
48. Steven W. Dean, John K. Potte, Richard a. Yetter, Tim David, Victor Kenneth Champegne Jr., Matthew Trexler, "Energetic intermetallic materials formed by cold spray." *Intermetallics* 43 (2013) 121-130.<https://doi.org/10.1016/j.intermet.2013.07.019>
49. W. Bao, Z. Deng, S. Zhang, Z. Ji, H. Zhang, "Next-generation composite coating system: nanocoating," *Frontiers in Materials* 6 (2019) 456324. <https://doi.org/10.3389/fmats.2019.00072>
50. Qiang Zhu, Ming Hui Chua, Pin Jin Ong, JohnathanJoo Cheng Lee, Kang Le Osmund Chin,Suxi Wang, Dan Kai, Rong Ji, Junhua Kong, Zhaogang Dong, Jianwei Xu, Xian Jun Loh, "Recent advances in nanotechnology-based functional coatings for the built environment." *Materials Today Advances* 15 (2022) 100270. <https://doi.org/10.1016/j.mtadv.2022.100270>
51. YuxingBai, Haiping Zhang,Yuanyuan ShaoHui Zhang, Jesse Zhu, "Recent progresses of superhydrophobic coatings in different application fields: An overview." *Coatings* 11.2 (2021) 116. <https://doi.org/10.3390/coatings11020116>

52. IndraneeDas, Goutam De, "Zirconia based superhydrophobic coatings on cotton fabrics exhibiting excellent durability for versatile use." *Scientific reports* 5.1 (2015) 18503. <https://doi.org/10.1038/srep18503>
53. S. Venkataraj, J. Geurts, H. Weis, O. Kappertz, Njoroge, W. K. Jayavel, Matthias Wuttig, "Structural and optical properties of thin lead oxide films produced by reactive direct current magnetron sputtering." *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* 19.6 (2001) 2870-2878. <https://doi.org/10.1116/1.1410948>
54. Pengtao Gao, L.J Meng, M.P dos Santos, V Teixeira, M Andritschky, "Characterisation of ZrO₂ films prepared by RF reactive sputtering at different O₂ concentrations in the sputtering gases." *Vacuum* 56.2 (2000) 143-148. [https://doi.org/10.1016/S0042-207X\(99\)00199-2](https://doi.org/10.1016/S0042-207X(99)00199-2)
55. C. M. Lopez, N. A. Suvorova, E. A. Irene, A. A. Suvorova, Saunders, "ZrO₂ film interfaces with Si and SiO₂." *Journal of applied physics* 98.3 (2005). <https://doi.org/10.1063/1.1994938>
56. H. H.Zhang, C. Y. Ma, Q. Y. Zhang, "Scaling behavior and structure transition of ZrO₂ films deposited by RF magnetron sputtering." *Vacuum* 83.11 (2009) 1311-1316. <https://doi.org/10.1016/j.vacuum.2009.04.041>
57. KaykhosrowKhojier, HadiSavaloni, Fatemeh Jafari, "Structural, electrical, and decorative properties of sputtered zirconium thin films during post-annealing process." *Journal of Theoretical and Applied Physics* 7 (2013) 1-7. <https://doi.org/10.1186/2251-7235-7-55>
58. Shi Gang Wu, Hong Ying Zhang, Guang Lei Tian, Zhi Lin Xia, JianDa Shao, ZhengXiu Fan, "Y₂O₃ stabilized ZrO₂ thin films deposited by electron-beam evaporation: Optical properties, structure and residual stresses." *Vacuum* 83.2 (2008) 366-371. <https://doi.org/10.1016/j.apsusc.2006.02.044>
59. M. Matsuoka, S. Isotani, J.F.D. Chubaci, S. Miyake, Y. Setsuhara, K. Ogata, Kuratani, "Influence of ion energy and arrival rate on x-ray crystallographic properties of thin ZrO_x films prepared on Si (111) substrate by ion-beam assisted deposition." *Journal of Applied Physics* 88.6 (2000) 3773-3775. <https://doi.org/10.1063/1.1286108>
60. H. Hasuyama, Y. Shima, K. Baba, G.K. Wolf, H. Martin, F. Stippich, "Adhesive and corrosion-resistant zirconium oxide coatings on stainless steel prepared by ion beam assisted deposition." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 127 (1997) 827-831. [https://doi.org/10.1016/S0168-583X\(97\)00015-3](https://doi.org/10.1016/S0168-583X(97)00015-3)
61. G. Sethi, P. Sunal, M.W. Horn, M.T.Lanagan, "Influence of reactive sputter deposition conditions on crystallization of zirconium oxide thin films." *Journal of Vacuum Science & Technology A* 27.3 (2009) 577-583. <https://doi.org/10.1116/1.3119669>
62. DeplaDiederik, StijnMahieu, *Reactive sputter deposition*. Vol. 109. Berlin: Springer, 2008.<https://doi.org/10.1007/978-3-540-76664-3>
63. JoonheeJeong, Kijung Yong, "Temperature programmed desorption study of Zr-diethylamido precursor for ZrO₂ CVD." *Journal of crystal growth* 254.1-2 (2003) 65-69. <https://doi.org/10.1116/1.3119669>
64. R.G. Gordon, J. Becker, D. Hausmann, S. Suh, "Vapor deposition of metal oxides and silicates: Possible gate insulators for future microelectronics." *Chemistry of materials* 13.8 (2001) 2463-2464. <https://doi.org/10.1021/cm010145k>
65. Y. D. Shen, X. L. Deng, H. P. Feng, R. Q. Gong, L. Ren, Y. B. Wang, Y. L. Zhang, W. N. Du, M. Y. Zhang, "Crystallization behaviours regulations and thermostability enhancement strategy of polypropylene composites modified by dispersed rice husk charcoal," *Journal of Polymer Research*, 10.1007/s10965-024-04028-x, 31, 7, (2024).
66. Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., Ayrilmis, N., and Alavudeen, A. (2024). "Selection and processing of natural fibers and nanocellulose for biocomposite applications: A brief review," *BioResources* 19(1), 1789-1813.
67. Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., and Ayrilmis, N. (2023). "Use of hemp waste for the development of mycelium-grown matrix biocomposites: A concise bibliographic review," *BioResources* 18(4), 8771-8780.