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Critical Overview of Coatings Technology for Metal Matrix Composites

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Abstract

In recent years, coating technology has come into existence to fulfil the industrial demands. The coated product must be capable of operating in the extreme environment to face the various challenges posed by friction, corrosion, fatigue, temperature, erosion, and abrasion. The coating is applied to protect metallic surfaces to make sure lifelong safety for the performance of the product. Presently, there is a strong need to develop the advance and smart coating technology for corrosion protection for various applications. Thus, this review highlights the advance in coating technologies and their processes by considering their importance for corrosion protection of metal in all-around technical applications. Various coating techniques, such as thermal spray, electrochemical deposition, spark plasma sintering, along with state of the art technologies were discussed. Special attention is dedicated to analyzing the process and to enhance properties, such as mechanical strength, corrosion resistance, etc. A study of many conventional and recent surface modification techniques of composite material are reviewed and presented in this article.

Keywords Coating · Tribology · Metal matrix composite · Corrosion · Decomposition · Spray · Sintering

1 Introduction

In the field of material manufacturing, researchers have revealed the tremendous efficient properties of metal matrix composites (MMC). Due to the presence of metal as one of the mandatory constituent of composite, mechanical and structural properties are of MMCs offer widespread applications in aerospace, automotive, sports and architectural industries. Resistance to wear, abrasion, corrosion, high temperature, along with rigidity, and high stiffness, are some of the remarkable properties of MMCs. Researchers have investigated various manufacturing techniques for the development of material for various industrial applications. MMCs have been specifically used in applications in the field of the automotive sector, including piston for diesel engines, cylinder bore, propeller shaft, brake parts. The success of MMCs application was found in 1990 by Honda [1, 2]. Thermal management produces 1million MMC parts annually. Al/SiC offered lower weight for the satellite microwave system. This includes printed circuit board cores, cold plates, etc. The last major market is for power semiconductor module base plates insulated gate bipolar transistors and laser diodes [2, 3]. From 1999 MMC market covered 5% by mass and 14% by value. An aeronautical component includes anal fins, fuel door cover on fighter aircraft, rotor blade sleeves, and swashplate; these parts are manufactured from Al composites. The Ti/SiC material is used for nozzle actuators links in many aircraft engines [2]. The industrial application comprises 6% by mass and 13% by value of the MMCs market. Industrial applications like cemented carbide electroplated, impregnated diamond tools, Cu and Ag MMC for electrical arrangements, etc. Recently, a new growing demands for the MMCs as in special applications whereas hardness and resistance to wear is primary importance. MMCs are used in a wide range of industrial operations

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such as piercing, circumrotary, hot metalworking, and drawing, forming and punching. Other items include impact dies, check valves, extruder nipples; hot forging die inserts [3, 4]. Besides, wear resistance is a complicated feature of material which depends on microstructure arrangement, chemical formation, surface hardness and coefficient of friction. Within surface engineering, the wear resistance and surface hardness can be considerably enhanced by adding the MMC coating layer.

Numerous surface modification methods were reviewed so far by the several research groups to enhance about the surface properties such as chemical vapor deposition, physical vapor deposition, laser beam cladding, electro-deposition coating, thermal spraying, etc. A very serious concern in the thermal spraying methods is the utilization of suitable coating materials. The method of producing coating materials has a certain impact on the opportunities of their application for various thermal spraying technologies. The tribological performance of coating materials has been challenging to understand just by taking into the record (surface hardness). As hard coatings do not adequately decrease the friction coefficient and may not defend the adjacent surface roughness. Whereas, in wear, rougher and dense particles from the sliding surface could be quickly stripped off and thereby provoking destructive abrasive wear. Hence, it is important to consider and utilizes solid lubricant coatings technology that may diminish friction, wear, corrosion, erosion, tribocorrosion, high temperature and high pressure in extreme environmental conditions and enhance the mechanical properties of coatings [4–6]. The present study offers a critical overview of the state of the art coating processing and their influence over MMC.

2 Processing Techniques of MMC

2.1 Powder Metallurgy

Powder metallurgy [7] is generally used to enhance the mechanical and tribological properties of the material [8]. The detailed summary of work carried out in the field of powder metallurgy is depicted in Table 1.

Table 1 Brief summary of the work carried out in the field of powder metallurgy

References	Material system	Powder size (μm)	Significant findings	Applications
[7]	$Ti+B_4C+Al$	22.4	Improvement in the micro-hardness of 754 HV and an average of 640 HV	Wear resistance application
[8]	$MO_2C+Cr_3C_2+VC+C+Fe$	20	Successful production of high vanadium high-speed steel	Hot rolling section
[9]	W + SiC/Cu	8.6–30	Increase the thermal conductivity and flexural strength	Fuel cell or electrical resistive application
[11]	6061 alloy + $AlSi_6Cu_4$	–	Manufacturing of metal foam with a high fraction of porosity and closed-cell microstructure	Car sandwich panel, in the bumper, and side protection of the car
[12]	Zn + Ti + Mg	–	Used carbamide space holder technique for the production of open-cell Zn foam	Battery electrodes and fuel cell
[13]	$Mg+B+B_4C$	–	Ball milling method is used for the preparation of the material to increase the hardness of Mg	Light weight structural material used for automobile and aerospace application
[14, 15]	Commercially pure Al + SiC + Mg	38	In situ powder-metallurgy method is used to increase the micro-hardness	Industrial applications
[16]	$Al+TiB_2$	10	The planetary ball milling process is used for the preparation of powder, in that increase in the bulk density were observed with the addition of TiB_2	Light weight application
[17]	7075Al + SiC	15–30	Corrosion rate is found to decrease with the addition of SiC	Industrial applications
[18]	6061 Al alloy + SiC + Gr	19–149	Uniform distribution of particles was achieved with the decrease in wear rate	Electric and recreation industry
[20]	$Ca_{10}(PO_4)_6(OH)_2)+Ti$	50	Successful development of hydroxyapatite-Ti biomaterial	Orthopaedics and dentistry

Compacting is done under careful control of the atmosphere and most of the research work is done on Cu-composites/Al-composites [9] using the powder metallurgy method [10, 11]. Many of the researchers have successfully prepared the MMCs based on Mg, Ni, Ti, Ag, and Sn. Figure 1 shown the detailed process steps which include the mixing of the matrix with metal powder by grinding and some additives are added in it then the process is followed by compacting [19–23], sintering [24, 25], machining and then will get the final product. Apart from the process step, the main goal was to gaining good reinforcement by proper distribution of metal powder in the source material and coordinating must be done of reinforcement and the matrix [8].

2.1.1 Mixing and Sintering

MMCs are processed using these techniques are Cu-MMC, Al-MMC, Mg-MMC, Ag-MMC. In few situations only mixing of the powder particle is used as the finished product but after realizing many of the critical arguments such as proper dispersion of filler in MMC and the intermediate bond between the filler in the MMC, the researcher had adopted the advance method for it. In the formation of MMC through the process like mixing, compacting and sintering, the one advanced and additional step is to coat with Ni, which will give good strength and wear resistance to the MMC materials [26].

2.1.2 Mixing and Compacting

Some of the investigators have used hot compacting of powder mixtures. Many of the investigators here found that the hot compacting method is very much incorrect for the manufacturing of MMCs as it results in clustering. Achieving better results in proper distribution of filler in MMCs, coating of Ni must be done with the help of electrolysis before the hot compressing [27], which will ultimately enhance the development in the mechanical and the wear properties of the composites.

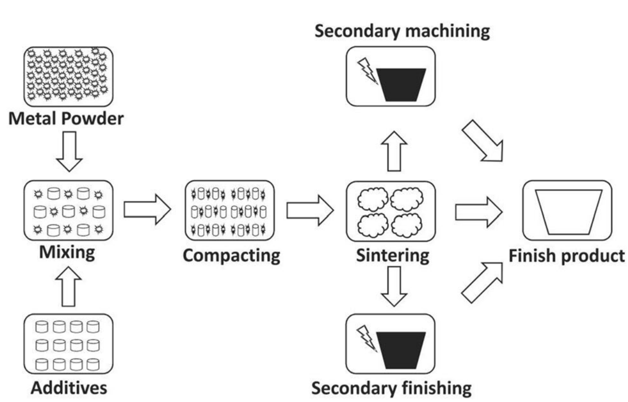

Fig. 1 Powder Metallurgy. Powder metallurgy consists of three main categories: 1. Powder mixing, 2. Compacting, 3. Sintering

2.1.3 Spark Plasma Sintering

Researchers have introduced a comparatively new method for synthesizing MMCs. Current is passed through a die and the powder, which will produce fast heating and the sintering rate gets intensified by this spark plasma sintering method [28–30]. The systematic concentration of powder can be accomplished in this process by spark impact pressure, electrical field diffusion, and joule heating. The method is commonly used for strengthening of powder, without granting plentiful time for grain growth. SPS is a high-temperature and high-pressure process, which will increase the strength and mechanical properties [31].

2.1.4 Distortion Method of Powder Compacting

To achieve better density many of the researchers have inspected the possibilities of deformation during powder compacting [32–34]. Cu-MMCs can be rolled as a better option than extrusion while considering their alignment in MMCs. It can identify the reinforcement quality of the product. With the help of the rolling process, the advancement in the wear resistance and the coefficient is observed. Al-MMCs can be processed with the help of hot extrusion of cold isostatic pressing and hot-pressed compacts. High-temperature results in the Al-MMC accumulation at the intersection. Recently, a new technique, ball milling of powder mixture is used to improve the properties and also used for the fabrication by hot extrusion of the compact. Mg-MMCs are also being prepared by hot extrusion [35–37].

3 Coating Deposition Methods

3.1 Melting and Solidification

Figure 2 shows the most traditional method for the manufacturing of MMCs. Some of the researchers had employed the melting and solidification process for the manufacturing of MMC due to their high temperature for melting. Due to high temperature, this process can be chemically reacted to the surface of the composites. So that the reason it, generally preferred low melting point matrix material. Also, the time recommended for the solidification is greater than the melting of the phase change matrix, due to the significance of natural convection [38, 39].

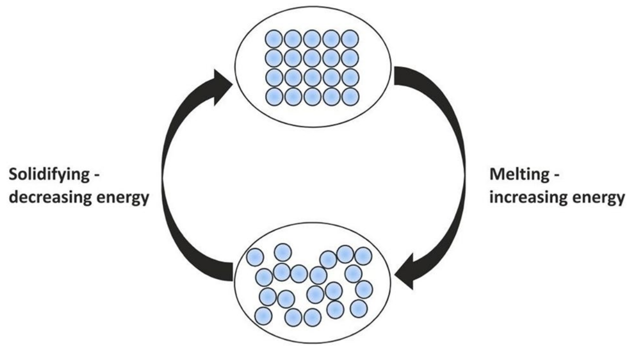

Fig. 2 Melting and solidification

3.2 Metal Infiltration

Melt infiltration technique is used to produce a composite network by creating a porous solid formation with dispersed reinforced material and then infiltrating liquid metal into the pores and then solidification. Figure 3 explains the metal infiltration in detail. Higher attempts of even spreading of the reinforcing material in the metal matrix which makes composite structure dense that is achieved by filling up the pores. High reinforcement volume fraction, uniform distribution and complex structures are achieved with liquid metal infiltration technique [40, 41]. In pressure infiltration process a molten metal or an alloy is injected in a mold and solidified with continuous or discontinuous reinforcement materials. Spaces between dispersed phase reinforcement get filled when dispersed phase reinforcement is soaked in the molten metal matrix. Either capillary force or an external force is applied to drive this infiltration process [42, 43].

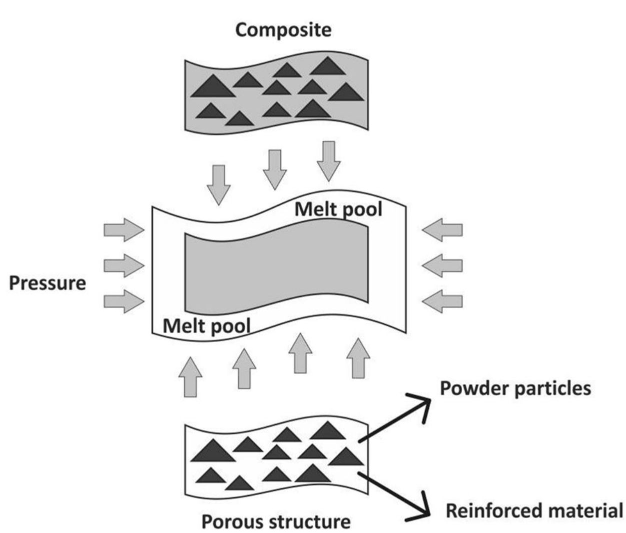

Fig. 3 Metal infiltration

3.3 Melt Spinning

The metal-spinning process is extensively used in the formation of amorphous and nano-crystalline alloy ribbons, as it manifests advancement in properties such as high efficiency, energy-saving, short and simple flow path [44, 45]. Figure 4 shows the melt spinning process. In this process, the melt polymer is poured into the metering pump to get it filtrated. Gradually pouring molten material drop by drop into the wheels forms a glass composite ribbon-like structure with the continuous rotation of wheels. The size of the metal–glass composite ribbon is 50 µm [46, 47].

4 Types of Coatings

4.1 Thermal Spray

Recently the automotive industry is seeking for lightweight materials to reduce vehicle weight to make it efficient as well as to reduce emissions [48, 49]. Thermal spray coating is the process in which molten or semi-molten metal is sprayed on the product's surface to form a coating as showed in Fig. 5.

The deposition of a coat on the surface is done by bumping and calcification. The main pro of the thermal spray coating is a large cooling rate, which offers the formation of amorphous structure in the coating. Classification of thermal spray process according to the heat source is flame spraying, plasma spraying, high-velocity oxy-fuel (HVOF) spraying or cold spraying. In the plasma spraying process, the main heat source is plasma which is formed by the ionization of inert gas by an arc struck between a tungsten cathode and concentric copper anode. In HVOF, the heat source is

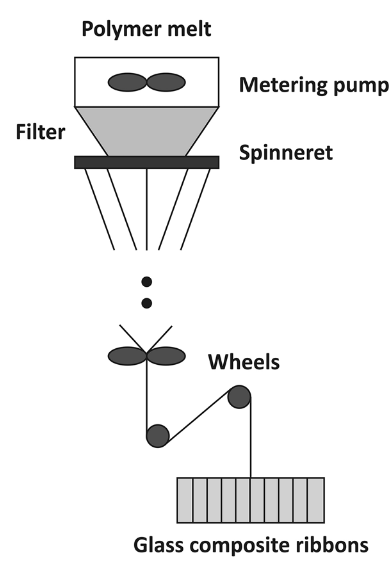

Fig. 4 Melt spinning

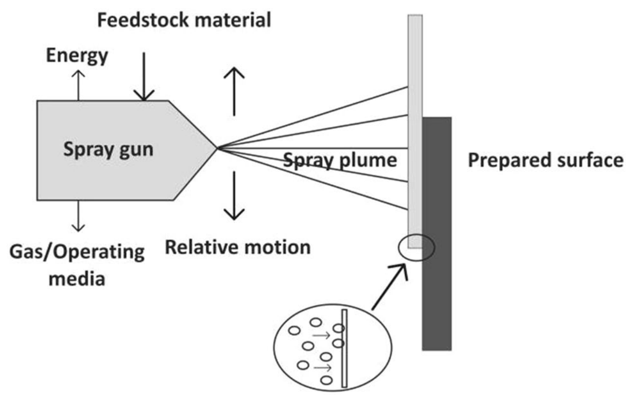

Fig. 5 Thermal spray coating

high-pressure combustion of a fuel–oxygen mixture. The fuel used such as propylene, methane, propane or hydrogen, or liquid such as kerosene. Bulk amorphous materials can also be coated with the help of thermal spray coating. Complex geometrical parts and intricate shapes are being coated by spraying on rotating mandrels. Thermal spray coating of Inconel 625 alloy is used in the application of anti-corrosion coatings in chlorine-containing environments [50] and NiCr/Cr_3C_2–NiCr coating is used for industrial applications where good corrosion resistance is needed with cost-effectiveness [51].

4.2 Electrochemical Deposition

Electrochemical deposition is the next most prevalent method following the powder metallurgy for its simplicity and effectiveness. The coating is done in the range from 20 to 180 µm microscopic levels [52]. This coating is used in applications such as nano-sensors [53], electrodes [54], and magnetic recorder head in computer applications. Two techniques are used for the fabrication of MMCs are electrodeposition and electro-less deposition. Figure 6 shows the electrodeposition method, in this method, electrochemical cells in which composite coating is installed by current flowing from cathode to anode.

The second technique is electro-less deposition, where metallic salts thermo-chemically decomposed in a bath with the release of metallic ions forming metal matrix composite [55, 56]. Villa-Mondragon et al. [57] proposed an excellent alternative of composite coating to protect the steel parts against wear. Martinez-Hernandez et al. [58] recommended a composite coating as a replacement to highly polluting coatings of hard Cr and Ni–B. Monteiro et al. [59] provided a composite coating to raise the hardness of the film. However, Table 2 summarised the comparatively impact on coating technology based on existing literature.

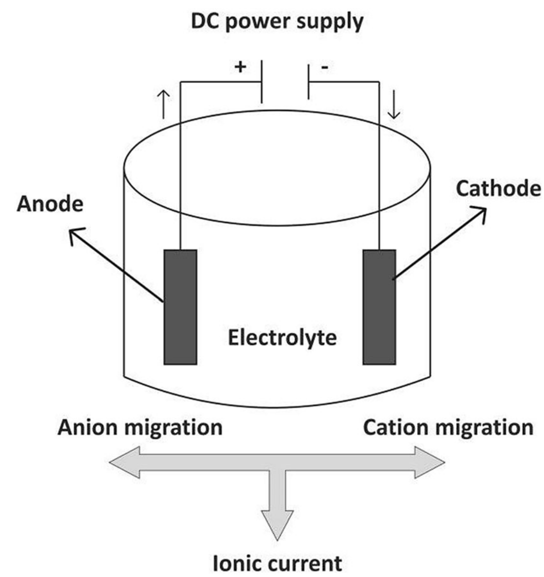

Fig. 6 Electrochemical deposition

4.3 Molecular Mixing

The corrodible sealing coating is ordinarily used in aircraft engines and gas turbine engines to magnify the efficiency of the compressor or turbine, to lessen the fuel loss, and to defend the rotating blade [60]. To avoid wear caused by rotating blades working at higher temperatures, the stationary parts are treated with coating [61]. Figure 7 illustrates the molecular mixing of MMC material. The process requires the reinforced material to be acid-treated and gathering them before injecting them into the metal salt bath, thus assisting the reinforcement material suspension and surface metal deposition on their surface. After adding all those material the bath is subjected to ultrasonic vibration to serve the reinforcement metal matrix. The prepared material is then passed through the oven at a specific temperature and then the reduction process is done in sequence to create the metal matrix composite powder [62–64]. Nie et al. [65] prepared a copper reduced graphene oxide, with the help of the molecular mixing process to enhance tribological properties.

4.4 Sputtering

Many of the new categories of coatings were introduced in the arena of nano-composites coating to intensify the mechanical properties that have shown the growing applications in the automotive, electronics, and space flights [66]. Some researchers have put efforts to manufacture MMCs by sputtering technique [67, 68]. The sputtering process is depicted in Fig. 8 shows the use of silicon wafers as substrates.

Table 2 Comparison between thermal spray and electrochemical deposition coating

References	Coating material	Substrate material	Coating size (µm)	Significant findings	Applications
Thermal spray coating					
[48]	Cr + Ni + Mo + Fe	Alumina	50	Coating provides high bond strength and thermal cycling resistance	Al brake rotor disks in the car and light trucks
[50]	Al + ZnAl + 625 Inconel alloy	Stainless steel 304L	10	Anti-corrosion coating in chlorine- containing environment	Marine application
[51]	Cr_3C_2	NiCr	20–30	Improved in corrosion behaviour and more economically preferred for industrial application	Corrosion protection application
Electrochemical deposition					
[53]	SnO_2	Alumina	6–100	The prepared film is suitable for gas sensing due to porosity and high surface area	Gas sensing devices/gas sensors
[54]	$NiCO_2O_4$	Ni foam	2–500	Interconnected mesoporous nano-sheets were electrodeposited on Ni foam which severed as binder-free and free electrodes conductive agent	Supercapacitor electrode material
[57]	SiC	Co-B	8–10	Sic coating can be applied to steel parts to protect against wear Excellent alternative to replace Cr coating	Machine fabrication, parts, and metal structures exposed to high stress
[58]	$COCl_26H_2O + H_3BO_3 + KCl$	Co-B	100	Alternative for Cr and Ni with smooth and shiny coating	Aerospace and automobile industrial tools
[59]	Ni–B with diamond nano particles	Steel	1–2	Gain improvement in hardness	Industrial application
[55]	Cr/AgNPs	Ni/AISI1018 steel	2.12 ± 0.02	Possess decorative, resistant, and anti-bacterial characteristics	Shopping carts, handrails or busses, railing, surgical material

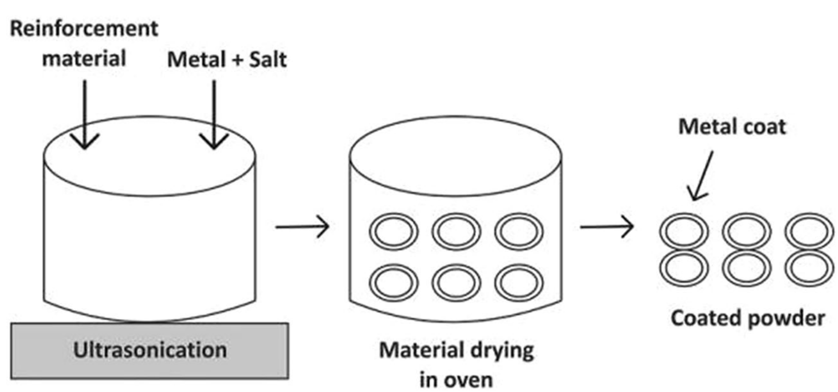

Fig. 7 Molecular mixing

In this process, the sputtering source metal has given positive supply, and the deposited material plate has given negative where the thin film of metal is created [69–71]. Arab et al. [72] and Ji et al. [73] fabricated a very thin

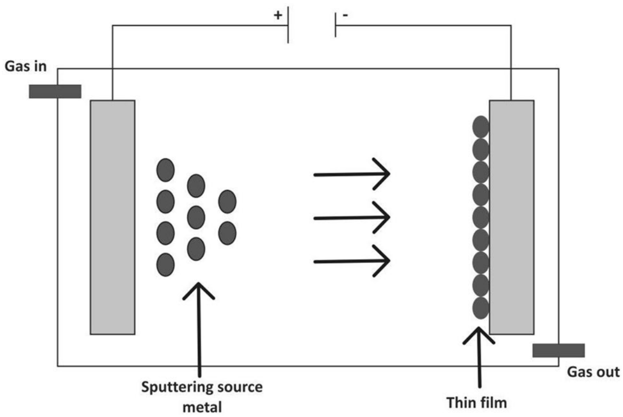

Fig. 8 Sputtering process

film of the nano-composite coatings by sputtering with loss effectiveness.

4.5 Vapour Deposition

An efficient way of countering the automotive parts from wear is the surface coating by the physical vapour deposition (PVD) and composite electrochemical coatings (CEC) techniques are the most widely investigated coatings process due to its versatility in tailoring physio-mechanical and tribological performance [74–76]. The coating by PVD is applicable where there are some chances of physical damage, so the coating should be even, pore-free, well clung, and self-healing [77]. The deposition of thermally vaporized material is done by the PVD coating process represented in Fig. 9.

The metal is vaporized at the vapor pressure of 1500 °C [78]. The evaporation is the extremely speedy process with deposition rates in mm/s, although, the quality of the film on substrates can suffer due to having less energy (around 0.2 eV) of evaporated particles [79]. The evaporated particles get to come across the plasma containing zone are ionized, and consequently capable of generating a denser film [80]. Li et al. [81] in 1992 first published the article of Ti–Si–N film, and the first report for the design of super hard Ti–Si–N nano-composites was from Veprek et al. [82]. Next, Veprek et al. [83] reported multiphase nanocomposite coatings with a hardness range from 80 to 105 GPa and proposed the lowest hardness to be 158 GPa [84]. Chemical vapour deposition (CVD) is the most reliable method for manufacturing sturdy coatings with a uniform layer [85, 86]. The layers of CVD are coated purposefully to improve oxidation, thermal resistance and also intensify the mechanical properties of coated materials. One of the major advantages of CVD is a simple implementation with low-cost precursors [87].

Figure 10 showing the CVD process where various temperatures, gas flow, and pressure is selected based on the requirement. The electron probe micro-analyzer implemented with a wavelength-dispersive spectrometer is used to determine the coating's chemical composition [88, 89]. Table 3 shows manifest the researcher done in the area of various novel techniques.

4.6 Plasma Spray Coating

For the improvement of surface characteristics like hardness, resistance to wear and corrosion, thermal and electrical insulation; a plasma spray method is one of the commercial coating methods employed to coat the automobile parts. Coating ductility is improved as it provides uniform deposition [91–94]. Plasma spray coating is being a clean, economic, and eco-friendly process, which also provides greater flexibility over powder particle size from 5 to 100 mm [95]. Figure 11 represents a schematic of the plasma spray coating process. Plasma spray process is employed to coat 250 mm thick TiO_2 coating on the Al/SiC substrate. The bonding coat of Ni–Cr alloy is also applied to improve the adhesion of the coating with the substrate [96–104].

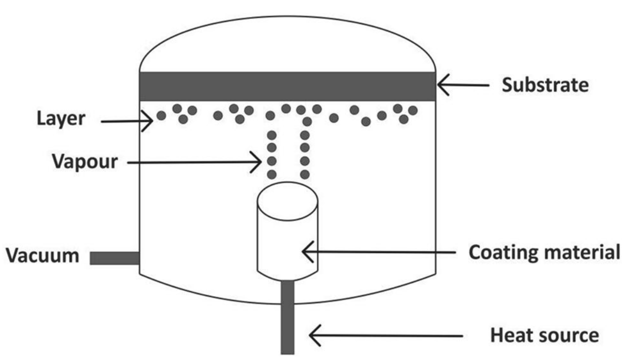

Fig. 9 Physical vapor deposition

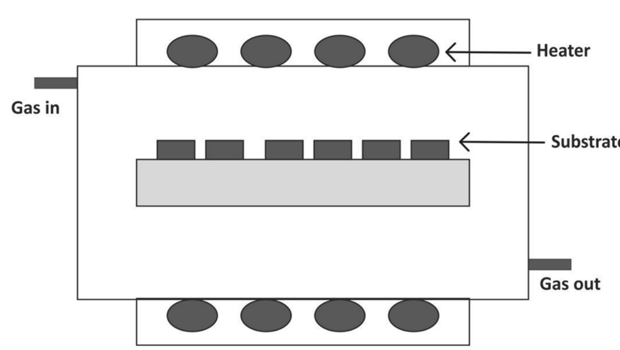

Fig. 10 Chemical vapor deposition

Table 3 Influence of various novel techniques on the coating system

References	Coating material	Substrate material	Powder size (μm)	Significant findings	Applications
Molecular mixing					
[64]	Cu	Carbon nanotubes	2	Coated material has eight times higher efficiency than SiC particles and three times higher than SiC whisker	Reinforcement of composite material
[90]	GO	Alumina	1–500	Enhancement in mechanical properties	High strength application
[65]	GO	Cu	1–100	Improvement in tribological properties	Electrical sliding contacts, such as brushes, bearing and contact wire
Sputtering					
[69]	TiNla-C	Steel	1.5	Enhancement in corrosion resistance property	Industrial applications
[70]	ITO	Silica	0.300–0.320	Deposition of ITO coating can be used as a hard transparent electrode	Solar cell or tablets
[71]	Bismuth	Cu(ln,Ga)Se_2	3	Enhancement of the photovoltaic performance of CIGS	Solar cell
PVD					
[74]	TiO_2 and N-TiO_2	Glass	0.1–5.0 and 0.6–6.0	Shown high photocatalytic activity	solar cell and dielectric application
[75]	CuNP	Al 4015	26–54	Enhancement in optical properties	Thermal solar applications
[76]	Zn	Mg alloys (AM50)	–	Lower weight and excellent mechanical properties	Automotive components
[77]	Ti	Stainless steel	50–200	Increased in hardness and elastic modulus	Manufacturing of load-bearing parts
CVD					
[81]	Ti–Si–N	HSS	10	Increase the hardness and shows glass-like structure	Cutting tools, dies and bearings
[82]	TiN, Si_3N_4, $TiSi_2$, nc-TiN, and nc-$TiSi_2$	Steel	3–20	Material having an enhancement in some properties like high hardness, high fracture toughness and elastic recovery	Industrial applications
[86]	Ni	Graphene nano-flakes	50–100	Used Raman technique to synthesis graphene nano-flakes	Nano-electronics

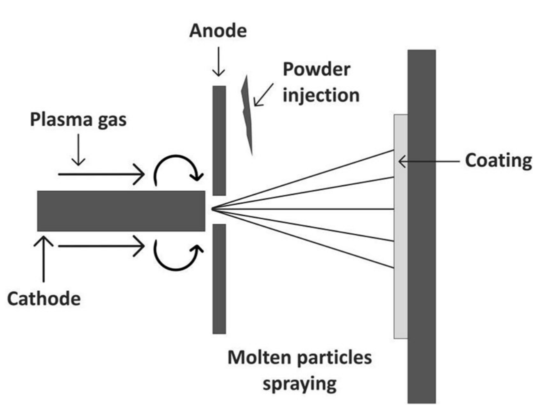

Fig. 11 Plasma spray coating

4.7 Plasma-Induction Polymeric Coating

For a variety of applications, particularly non-thermal plasmas, enable one to have a controlled process of depositing polymers on any substrate. The highly cross-linked structure is associated with good mechanical resistance [105, 106]. Figure 12 shows the plasma induction polymeric coating, which is similar to the conventional polymerization process. Polymer retains the structure of its starting material in plasma induction, whereas in plasma polymerization the product will have an entirely different structure and the starting material serves only as a source of radicals for the polymerization to proceed.

In plasma-induced polymerization, the starting material must contain polymerizable structures such as olefinic double bonds, triple bonds, or cyclic structures. Plasma

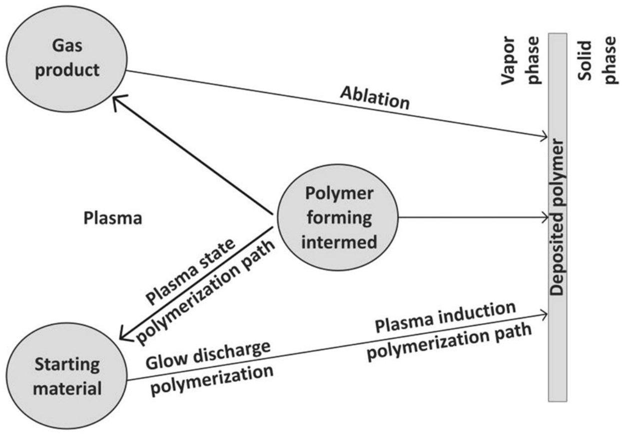

Fig. 12 Plasma-induction polymeric coating

polymerization has multiple steps involving intermediate species, whereas in induction polymerization step by step reaction takes place. By-product does not form in the plasma induction polymerization process, the reaction between the solid product and reactive gaseous intermediates do not disturb its kinetics [107–113].

4.8 Laser Cladding

Laser cladding is a surface improvement method that practices a powerful laser beam as a heat source to melt supplementary material along with a vital portion to form a homogeneous alloyed surface layer with new phases and compositions [114–123].

The method is carried out in two steps; Fig. 13 shows the laser cladding process. In the first step, a separate layer was deposited to investigate the processing window of multilayer laser cladding. The intensity of the laser beam is uniformly distributed in the cross-section perpendicular to the propagation direction and the powder flow is provided with the help of a nozzle. Each laser layer was deposited in six layers. To reduce the number of cladding experiments the gradient technique was applied [124–129]. In the second stage, optimized processing parameters are used to coat the overlapping of the laser pathways. After overlapping the laser pathways the coating was cut along the cross-sectional direction, polished and preparing the samples for the morphological investigation like SEM and EDS [130–140].

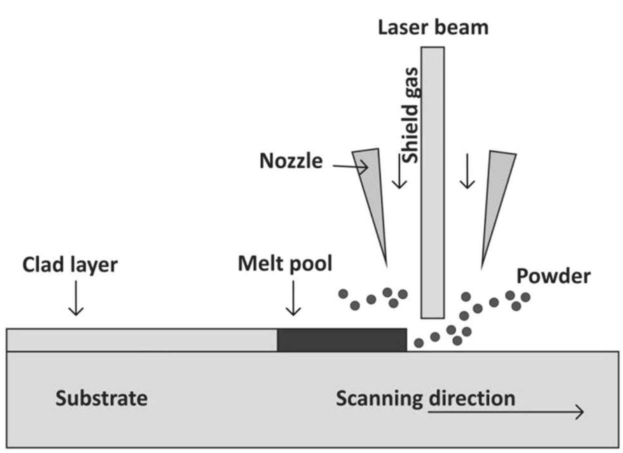

Fig. 13 Laser cladding

4.9 Electro-deposition Coating

Figure 14 shows the enhancement of the surface properties of the material by the electrodeposition coating process. The surface of the material plays a very vital role in many applications [141–145]. Many of the components of machine abandon due to defects such as wear, corrosion, and fatigue. The properties like tribological, mechanical and corrosion resistance get improved by the coating the reinforcement material on it [146]. The surface to be coated is connected to the cathode and the coating material is connected to anode during the electro-deposition process [147–151]. Coating provides a broad range for a variety of different automobile and industrial applications due to more favourable tribological and corrosion properties [152–155]. Table 4 describes the types of coating technologies in detail.

5 Types of MMC and Their Coating Processes

5.1 Aluminum MMC

Aluminum MMCs are extensively used in various fields like aircraft, aerospace, automobiles [156–158]. High strength and lightweight are the demanding applications of aluminum alloys. Some of these applications could be in wrought form. The components that compose the major surface property are the wear resistance. All aluminum alloys exhibit poor

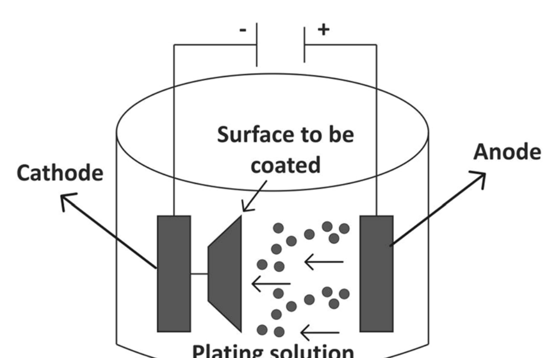

Fig. 14 Electro-depositing coating

Table 4 Investigation done in the region of coating technology

References	Coating material	Substrate material	Powder size (μm)	Significant findings	Applications
Plasma spray coating					
[92]	Ti	Magnesia-stabilized zirconia	0.10–0.50	Obtained higher shear strength with smooth surface finished	Biomedical applications
[93]	Hydroxyapatite– tantalum	Mg alloy (ZK60)	10–50	Improvement in corrosion resistance and surface hardness	Orthopaedic bio-implant applications
[94]	$10TiO_2$ -Cr_2O_3	Steel	–	Enhancement in the mechanical properties	Turbine
[95]	Ni	1018 Steel	45–56	Increment in the mechanical properties	Industrial applications
[97]	$Ba(Ni_{1/3}Ta_2/_3)O_3$	Steel/alloys of metal	1–5	Excellent phase stability	Anti-oxidation protection of gas turbine engines hot-section components
[100]	hafnium-carbide (HfC)	Copper	110	Enhancement in the thermal shock and oxidation resistance of materials under ultra-high temperature environments	Thermal ablation field
Plasma-induction polymeric coating					
[108]	Al	Cu	0.5–2.5	Modified the bactericidal properties of polymer	Industrial applications
Laser cladding					
[113]	$Ni+Y_2O_3$	Ti_6Al_4V Alloy	4–100	Micro-hardness is enhanced by three times than the titanium	Automobile manufacturing, aerospace, biomedical devices and petrochemical industries
[115]	Ni45 and Mo	H13 K	50–100	Enhancement in the micro-hardness of the material	Widely used in manufacturing industries
[116]	Zr	Metallic glass (MG)	20–500	Improvement in hardness and corrosion resistance	Biomedical Implant Application
[117]	ZrO_2 and Al_2O_3	Ti_6Al_4V alloy	5–10	Improvement in the biocompatibility of the material	Applied to load-bearing applications
[118]	Ni60 + C+TiN + Mo	Ti_6Al_4V Alloy	50–100	Enhancement in the wear properties of the material by 26.7 of titanium	Automotive and aerospace industries wear high specific strength is required.
[122]	TiN	1020 steel	1–100	Exhibited higher hardness and wear resistance	Material engineering applications
[125]	Fe-Cr_3C_2	35CrMo Steel	50–100	Improvement in the wear resistance of the material	Industrial applications
Electrodeposition coating					
[143]	Ni–Al_2O_3	Mild steel	100	Improvement in the surface properties of the material	Any type of engineering materials
[144]	Ni–TiC, Ni–TiN, and Ni–TiC–TiN	Tungsten carbide	5–12	Improvement in the anti-wear characteristics of the coated material	Cutting tool coating
[145]	Zn–SiC	Alloy	5–500	Smooth surface finished is obtained	Industrial application
[143]	Ni–Al_2O_3	Mild steel	2–100	Improvement in the surface properties of the material	Automobile and industrial applications.

Table 4 (continued)

References	Coating material	Substrate material	Powder size (μm)	Significant findings	Applications
[153]	Mn/Co	Steel	20–200	Enhancement in the electrical resistance of the material	Solid oxide cells stacks

tribological characteristics, due to these limited the applications of aluminum alloys in many sliding components, tools, and parts that are requiring wear resistance [159–164]. The main reason for such poor tribological properties is the low surface hardness and high friction coefficient of aluminum alloys. For adequate wear resistance, the surface should be rigid. To improve the hardness of the material some hardening techniques should be employed like surface coatings. To advance the wear resistance of the component many surface technologies, such as a hard anodizing, electroplating, and physical vapor deposition, have been applied [165, 166]. Powders of carbides or other refractory phases have been added to reinforce the surface coating layers on aluminum alloys to enhance the surface performance of aluminum alloys [167, 168]. Variety of surface modification techniques are available like laser cladding [114–123], plasma spraying [91–95], vapour deposition [74, 157]. Among all these techniques laser cladding is largely used for surface modification [169, 170].

5.2 Copper MMC

Cu-MMCs are having higher thermal conductivity and extraordinary tribological properties, so broadly employed to many sorts of applications [171, 172]. The answer to the broad application of Cu-MMCs is the property modification of reinforcement components [171]. B [173, 175], Cr [173, 174] and Ti [174, 176] are the alloying metal matrix with elements to develop the interfacial bonding. Most of the alloying elements with metal matrix have shown a remarkable impact on the thermal conductivity of the matrix material. It has been noted that the high thermal conductivity is accomplished in Cu matrix composites reinforced with Cr-coated alloying element particles [176, 177]. The surface modification technique used for these Cu-MMCs is electrodeposition coating [52].

5.3 Nickel MMC

Ni-MMCs coating having outstanding corrosion and wear resistance so it is used frequently [178]. Currently, nickel films plated on reinforcements have been used to improve the adhesion and wettability during composite fabrication [179]. The electro-less process offers a coating of nickel by chemical reduction of nickel ions onto the catalytic surface. The reaction continues as long as the surface remains in contact with the electro-less nickel solution as the coat itself is catalytic to reduction. Uniform coating over all surfaces, regardless of size and shape is obtained by this nickel MMC coating. The nickel MMC coating also improves the property of weldability as compared aluminum MMC coating. The electro-less coating technique is mostly used for surface modification in Ni-MMCs [178].

5.4 Magnesium MMC

Mg-MMCs having high specific strength and low density as compared to other structural metals, so it is accepted commercially. It not only has the lowest density of all metal elements, but it is also very strong, highly resistant to corrosion and efficiently machinable [180]. Due to poor hardness, low ultimate strength and wear resistance the utilization of Mg alloys is reduced [181, 182]. To improve the properties, the proper selection of reinforcement of material is made. In Mg-MMC, fiber distribution is important to enhance mechanical properties [183, 184] and also the electro-spinning technique is mostly used for surface modification in Mg-MMCs [185].

6 Properties Affecting on MMC Coating

6.1 Wear and Friction

Wear and friction are the very important property for coating and many of the wear studies are on Ni-MMCs coating prepared by electro-less or electro-deposition techniques [186]. Some of the studies on Cu-MMCs and Al-MMCs are also present. In the development of wear resistance and reductions in COF, MMCs reinforcement material plays a very crucial role. The maximum change in wear properties had shown by the powder metallurgy technique [7, 8] using Ni-MMCs. Molecular-level-mixing technique had also served to advance the wear properties of Cu-MMCs, occurring reduction in wear loss [60, 61].

6.2 Hydrogen Storage Properties

Hydrogen (H) is the most stimulating option of a clean energy source because it contains huge energy as compare to other chemical fuels [187]. Due to this advantage, H energy can be applicable in automobiles. The effective use of H energy is important to promote reliable and effective H storage systems. Presently, several species of H storage materials are investigated, such as metal hydride systems [188], and nano-fibers [189–191], etc. H storage materials have the scarce pleasanter H-storage capacity and absorption–desorption rate than Mg-MMCs [187]. The US Department of Energy had set a goal of 6.5 wt% content of H storage for commercial applications [192]. Some of the methods to increase the H sorption properties such as ball milling [193, 194], metal catalysts [195, 196] addition or H storage materials [197–199].

7 Conclusions

Numerous coating deposition technologies have been developed till date by the researchers to protect the material from wear and corrosion nevertheless very few of them succeeded as the technical realization of coating technologies within an industrial scale is very challenging with respect to surface engineering. The presented work summarizes various surface modification techniques, parameters affecting the microstructure of material, properties (like mechanical, tribological, thermal, etc.) of deposited material along with the structure of the coating. Moreover, numerous coating technologies were studied with their specific applications, some of the important aspects are as follows:

- Complex geometrical parts with intricate shapes were being coated with the assist of thermal spray coating.
- Enhancement in the properties like mechanical, tribological and thermal can be achieved with the employment of PVD and CVD as they produce denser films. The PVD surface with the addition of surfactant based solution is found to be the desirable method for controlling tribological losses.
- Plasma spray coating helps alteration of structural patterns surface by applying Ni–Cr alloy to improve adhesion of the coating with the substrate.
- Laser cladding process provides very thin layer of uniformly distributed coating with the help of laser beam.

There are enormous processes of coatings technologies accessible for protecting metal and alloys. Still, the popular uses of metal in the automotive industries are stopped by the lack of relevant protective coatings that can resist severe service conditions. A vast deal of research is yet required to produce more reliable, manageable, and affordable coating technologies.

Compliance with Ethical Standards

Conflict of interest No conflict of interest exits in the submission of this manuscript.

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