International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XIV No. 2 / 2022
https://doi.org/ 10.54684/ijmmt.2022.14.2.128

COATED POLYMERS -A REVIEW

Alina Mărguță, Simona-Nicoleta Mazurchevici, Dumitru Nedelcu

"Gheorghe Asachi" Technical University of Iasi, Department of Machine Manufacturing Technology, Blvd. Mangeron, No. 59A, 700050, Iasi, Romania

Corresponding author: Simona-Nicoleta Mazurchevici, simona0nikoleta@yahoo.com

Abstract: The coating of polymers with different particles has become an important research direction due to the substantial increase in properties and implicitly the use of products in several industrial fields. The objectives of this review paper focus on polymers coating with different ceramic and metal micro particles. Thus, during the first part are presented the main methods of coating (with method detailing, advantages and disadvantages, usage materials and potential industrial applications). After this part the APS - atmospheric plasma spraying technology is detailed because it is one of the most used method. Going forward there are presented some studies from technical literature that analysed different aspects of powders coating onto biodegradable substrates (like polymer) such as structural and morphological analyses, tribological and adhesion tests, corrosion resistance, electrical conductivity, influence of process parameters and their optimization and so on. Thus, the present paper aims to briefly resum researchers' concerns on the coating of polymer-based materials, which has reached in the last period the attention due to their capability and functional applications.
Keywords: polymers, coating, PVD.

1. INTRODUCTION

The samples obtained from materials with a polymer matrix (whether they are composite or not) are relatively competitive materials that find their applicability in most sectors of activities. Their huge use is due to their high strength-to-weight ratio compared to classic materials such as metal, wood, glass etc. However, a fundamental requirement is high reliability, polymers being limited in use in some industrial applications that involve high working temperatures and wear, [1, 2]. In order to reduce the surface degradation and increase the thermal resistance of the polymer surfaces, the researchers found a viable solution, covering them with ceramic or metal microlayers depending on the intended application and their operating conditions. Thus, ceramic coatings have been widely used for many applications in order to improve resistance to wear, corrosion, oxidation and heat [3–6]. Metal [7] and cermet powder coatings have been shown to be effective to improve the wear resistance of polymer matrix materials.

The coating of polymeric surfaces can be achieved by using several methods, the best known of which are: TS - thermal spray, [8, 9], PVD - physical vapor deposition, electroplating, [10, 11] and CVD - chemical vapor deposition, [12, 13]. It is expected that any of these methods will present advantages but also limitations, depending on the factors involved in the coating process. Thus, before the coverage is achieved, regardless of the selected method, a systemic analysis is carried out in order to identify the controllable factors that radically influence the quality of the samples to be obtained. First of all, the process parameters related to the material - substrate and surface conditioning are analyzed, as follows: the parameters related to the coating powder (chemical composition, particular size, powder flow rate), to the gas (its nature, temperature and pressure), and scanning (spraying distance, speed, number of passes). Other factors that need to be mentioned are: substrate temperature and its oxidation, particles impact energy and particles temperature. Establishing the controllable factors, mentioned previously, have a significant influence on the output factors related to the quality of the coating: porosity, microhardness, composition, deposition efficiency, adhesion strength, electrical conductivity, surface roughness etc.

In the technical literature, the main researches on coatings with ceramic/metallic micro particles refer to the surface characteristics of the deposited micro layers (wear, layer adhesion, corrosion, hardness, etc.), [14-17] but also to the influence of the process parameters and the optimization to them, [18].

The present work aims to present a current state of the art regarding the technologies used to achieve coatings with ceramic/metallic powders on polymeric substrates. Also, the most important aspect followed in the analyzed references are the types of determinations that aroused the interest of the researchers. Another important aspect is that of the input parameters, which is also the subject of one of the chapters of this work.

The thermal coating process of polymer materials finds its applicability in fields such as automotive, aerospace and marine industries, to improve the

wear/corrosion resistance and service life of parts such as pistons, cylinders, valves, turbine blades), [19-21]. APS (Air Plasma Spray) is considered one of the most used thermal deposition techniques, and coatings obtained by zirconium and chromium are widely spread in mechanical applications, [22]. The main disadvantages of these coatings are given by micro-cracks, poor insulation and residual stresses (which occur during the cooling process), [23].

High purity Al_2O_3 (aluminum oxide - alumina) powder is used for plasma spraying coatings. This type of coating has good dielectric and thermal characteristics. Moreover, the coatings are wear resistant, have higher hardness, high temperature stability and are chemically inert. The ceramic coating is suitable for electronic and semiconductor applications, electrostatics, capacitors, vacuum chambers, etc. The high purity of the material ensures non-contamination of the semiconductor components, [23]. Also, elements such as nickel, zirconium, aluminum, molybdenum and chromium are good choices for applications that require high hardness with moderate wear and corrosion resistance.

It is known that the addition of ceramic particles or metal particles to a substrate will provide a combination of properties of all three types of materials: biopolymer matrix, metal reinforcement components, and ceramics. This can lead to the improvement of the physical and mechanical properties of the composite, [24].

In the specialized literature, the main researches refer to the anti-corrosion protection characteristics. There are studies that refer to the main ways of working, procedures for preparation and applications, [25-31], a comparative analysis of all factors is necessary to understand their applicability in practice.

Also, researchers' interest has focused on electromagnetic effects, [32], applications with actuators, sensors, [33-36] and shape memory materials, [37, 38]. These materials also provide insights for biomedicine, [39, 40], mass media etc., [41–43].

The surfaces of the samples made of polymeric materials are coated with metal, ceramic powders using several methods. Among the most used are: physical vapor deposition (PVD), chemical vapor deposition (CVD), [12, 13], electroplating [10, 11] and thermal spraying (TS) [8, 9, 44]. All these techniques have inherent advantages and shortcomings [31]. The following table 1 highlights the main characteristics of each coating technology mentioned above, but also the main strengths and weaknesses of each.

Thermal plasma spraying (APS) – brief description

Plasma jet thermal spraying (APS) is part of TS technology - thermal spraying (table 1), [45]. The APS process involves introducing particulate raw material into the plasma jet to accelerate and fuse them with the deposition surface. The process is based on the formation of plasmogen by the dissociation and ionization of the gas in a high-power electric arc (about 80kW) between a cathode and a tubular anode. The speed of the generated gas is high, of the order of 1000m/s, because at the exit, the gas tends to return to the normal energetic state (lowest energy) forming again a strongly exothermic reaction, [45]. The main areas of use of this technology are closely related to the improvement of the surface characteristics of the substrate: resistance to wear (abrasion, erosion and friction); resistance to corrosion and oxidation; electrical conductivity or insulation; thermal or magnetic conductivity; biocompatibility etc. Figure 1 shows how the APS equipment works.

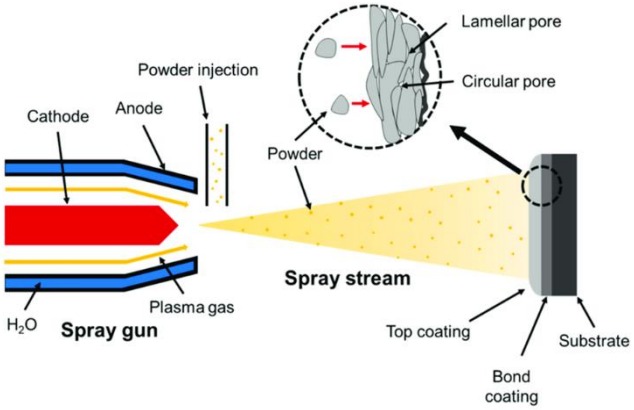


Fig 1. Schematic diagram of a thermal plasma spray (APS) equipment, [46]

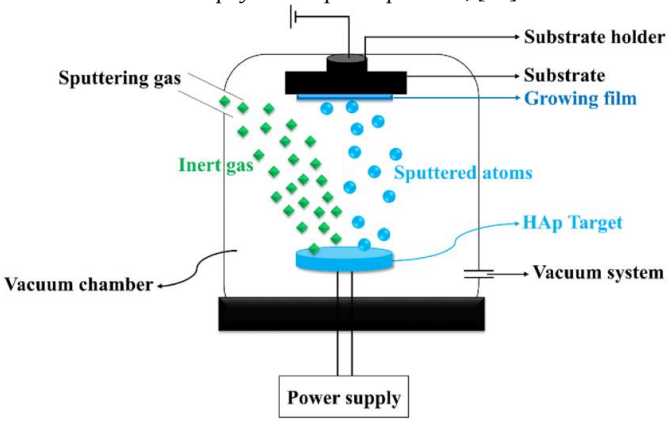
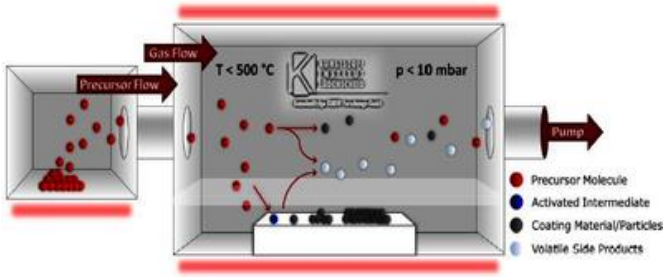
The main advantages offered by the APS thermal coating method are: increases the lifetime of parts/marks; cost reduction; reduced downtime / maintenance; increasing productivity; increasing product quality by improving functional characteristics.

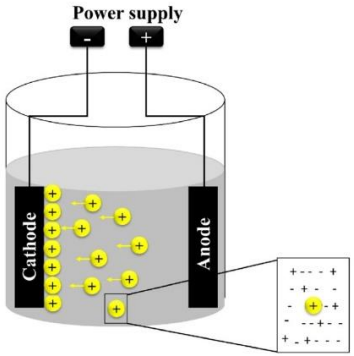
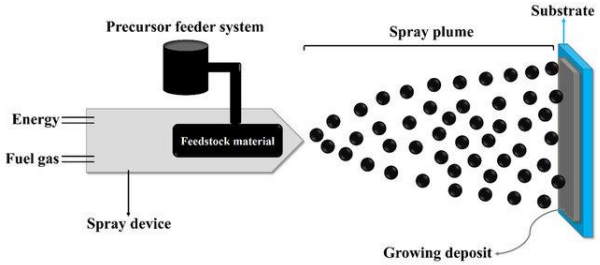
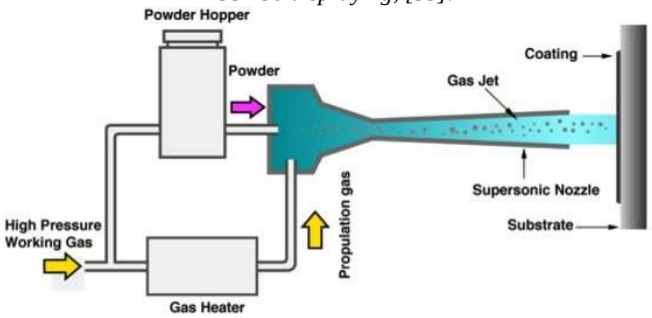
The disadvantages of the method are closely related to the high working temperatures that can affect the substrate (thermal degradation) and to the rapid cooling of the deposited powder due to the cold substrate with which it comes into contact. However, these disadvantages can be minimized by selecting an optimal spraying distance and time. As for the influence of the rapid cooling of the particles, it can be reduced if a preheating of the substrate is carried out.

The main classes of materials used for the deposition of layers using the APS method are:

Metal micro/nano-particles: Obtaining metal powder at the micro/nano level is achieved by synthesizing, [47], using constructive or destructive methods. Powders/particles can be obtained from almost all metallic materials (gold, silver, copper, aluminum, cobalt, zinc, cadmium, etc.).

Table 1. General characterization of the main coating methods, [48-52]

Coating scheme	Description	Details
PVD - physical vapor deposition, [48]. 	The PVD takes place under vacuum conditions, allowing the vapor particles to move towards the surface of the part, without colliding with the molecules of a gas that would be present in the enclosure. The particles condense on the target surface, forming a thin film. Moreover, the vacuum makes it possible to avoid any chemical reaction (for example, if we deposit copper, the presence of oxygen produces copper oxide, which will have a negative influence on the quality of the deposited layer, on the deposition time etc.), [48].	***Advantages and disadvantages:*** + environmentally friendly compared to electroplating and painting; + allows multiple coverage methods using the same technique; + does not require additional layers of protection; + large variety of powders that can be deposited; + good resistance; + superior durability; + good dimensional accuracy; - expensive equipment; - requires cooling systems; - defects: exfoliation, cracking; - it involves qualified personnel due to the high working temperatures and the control of the evacuated premises; - the coating does not create chemical bonds with the substrate; - quite low productivity. ***Material:*** organic or inorganic materials. ***Aplicații:*** manufacture of electric circuits and integrated circuits; transparent coatings; reflectors and optics; aerospace, automotive, surgical and medical industries, molds for all types of materials that can be processed, cutting devices, weapons etc.
CVD - chemical vapor deposition, [49] 	The CVD process involves exposing the surface of the part that serves as the substrate to volatile substances, substances that react in contact with the substrate, thus achieving the deposition of the layer. A classification of this process can be made according to the physical properties of the vapors: liquid phase for liquid or solid precursors, these being dissolved in a solvent and transported to the substrate similar to the CVD process; from the gas phase, by using a liquid/gas aerosol that transports the precursors to the substrate (chemical vapor deposition). The transported gas is also used to drive off volatile products that arise during the deposition process. Furthermore, chemical methods can be classified by operating conditions (atmospheric pressure, low pressure or high vacuum pressure). Chemical reactions lead to the absence of a distinct plane between the deposited layer and the substrate, as new molecules are generated and diffusion phenomena occur. The deposition step is carried out in a reactor, and the temperature is an important parameter that must be	***Advantages and disadvantages:*** + productivity; + allows the deposition of hard-to-evaporate materials; + good reproducibility; + allowing the creation of epitaxial films; + high adhesion; + high density, almost 100%; - expensive equipment; - complex procedure; - toxic and corrosive gases; - high temperatures. ***Material:*** metal or ceramic powders ***Applications:*** optical fibers, semiconductors and integrated circuits, sensors and optoelectronic devices, microelectronics industry (passivation layers, epitaxial layers, oxidation barriers, dielectric films, etc.)

	controlled during the process. For this reason, only source materials and substrates compatible with the reactor operating condition are suitable for the process, [49].	
EPD – Electrochemical deposition, [48]  	EPD is often performed in a two-electrode cell at a constant voltage. It is a well-known colloidal technique for making ceramic coatings in which charged suspended/dispersed particles move through a liquid medium to deposit on the conductive substrate. Usually, the size of suspended particles should not exceed 30 μm [53, 54].	***Advantages and disadvantages:*** + uniform thickness of the deposited layer; + quick deposit; + covers complex substrates; - low adhesion; - difficult to achieve crack-free coatings; - requires high sintering temperatures, [50]. ***Material:*** ceramic, metal. ***Applications:*** surface treatments and anti-corrosion-electroplating, aiming to protect the substrate by covering with a top layer**.**
TS - Thermal spraying, [49]  	During plasma spraying, which is performed in either an atmosphere or a vacuum environment, a direct current (DC) is established between the electrodes using a plasma-forming gas such as helium, argon, or hydrogen. It can melt or semi-melt the material to be deposited, as the temperature can reach 16000°C. These molten or semi-molten particles enter the spraying device to then be sprayed through a nozzle towards the substrate (target material).	***Advantages and disadvantages:*** + high spraying speed; + productivity; + low cost; - high temperatures induce degradation of the substrate; - rapid cooling produces amorphous, hard and brittle coatings, [50]. ***Material:*** metals, ceramics, alloys and composites. ***Applications:*** refinery plants, water tanks, aircraft engine cylinders, shafts, bushings, elements - gas turbines, pistons, dies, guide rollers, bearings, [51].
CS- Cold spraying, [53].  	The CS process is an additive manufacturing technique used to make new parts, repair structures and apply coatings with a high powder deposition rate. Solid metal powder is accelerated in a preheated gas stream and propelled toward a target. When the flux hits the target, the metal particles deform plastically and adhere to the surface, [55].	***Advantages and disadvantages:*** + low heating of the substrate, which is not thermally affected; + there are no structural changes to the substrate (phase changes); + the metal particles for deposition are not melted beforehand, reducing their oxidation; + homogeneity of the surface; + low porosity; + the simplest and cheapest deposit method; + resistance to compression; + productivity; + thin layer; - one of the constituents must be ductile (deformable). ***Material:*** Metals, alloys, polymers, ceramics and composites on a variety of substrate materials. ***Applications:*** bonding of two structurally different materials, strengthening of thin-walled structures.

Micro/nano-particles based on metal oxides: In order to improve the characteristics of micro/nanopowders, metal powders are synthesized. Their reactivity and efficiency is much superior to their metallic counterparts, [56]. Iron oxide (Fe_2O_3) is probably the best known metal oxide, which is formed when iron comes into contact with oxygen (from air, water, or another compound). The most used metal oxides are: aluminum oxides, silicon, zinc, titanium, cerium, magnetite.

Ceramic micro/nano-particles: As the name suggests, they are based on ceramic materials that possess special characteristics, the most important being refractoriness. Ceramic micro/nano-particles are inorganic solids that can be obtained from both metallic and non-metallic compounds. These were discovered in the early 1980s and were formed using a process called Sol-Gel, which mixes the particles of the base material into a solution and gel to form the ceramic micro/nanoparticles. Later methods involved their sintering, a process involving parameters such as pressure and temperature. The small size of the particles allows to obtain extraordinary properties. The larger the particles, the more defects appear, making them brittle. They can be found in different forms: amorphous, polycrystalline, dense, porous or hollow, [58]. Therefore, these particles are used globally by researchers in applications in various fields of activity, imaging applications, dye photodegradation, catalysis and photocatalysis, and others [58]. In medical applications, they are used, for example, to reconstruct bone parts; in engineering applications, for energy storage and supply. They also find their applicability in the field of constructions, the transport system, communication, due to the electrical characteristics, as it allows the transfer of energy with maximum efficiency.

2. EXPERIMENTAL ANALYZES USED IN COATINGS OF POLYMERIC MATERIALS

In table 2, some researches carried out in the field of plastic material coatings are presented. The greatest interest, according to the analyzed references, belongs to the coatings with metal powders that had the purpose of improving, increasing the functional characteristics of the substrates (polymers).

3. EXPERIMENTAL RESULTS ON THE COATINGS OF POLYMERIC MATRIX COMPOSITES (PMCS) WITH CERAMIC LAYERS USING APS

3.1. Aluminum oxide coating (Al_2O_3)

Before the deposition of the ceramic layer, an intermediate bonding layer (hereinafter referred to as the bonding coating) made of aluminum was deposited, with the role of increasing the adhesion of the upper layer to the polymer substrate.

Morphology and structure

Figure 2(a-b) shows the surface morphology of aluminum oxide (Al_2O_3) ceramic coatings that highlight layered spatters of pulverized alumina. Other features such as cracks, interlamellar pores and partially melted particles can also be observed [100]. On the surface of the coating, the presence of two types of structures specific to irregularly distributed ceramic deposits can be observed: coarse washes (in the form of pores or corals) and smooth and flat washes. To identify the chemical structure of the splats, an EDX analysis of the surface (indicated in the wheel borders) was performed, figure 2c and 2d. Following this analysis, it was observed that the structure of the two washes is similar, containing similar elements (Al and O), attributed to alumina. Thus, the possibility of successfully depositing aluminum oxide ceramic layers on a polymer substrate using APS technology was demonstrated. The fact that the two types of splashes are different (porous and smooth) comes from the different melting state of the particles.

Figure 3 shows the morphology of the surface coatings with Al_2O_3 for two different values of the intensity of the spraying current: (a) 300A and (b) 360 A, respectively. It is observed that for the sample in which a higher intensity of the current (b) was used the porous (coral) splats are less because, the particles had more energy when they exited the plasma flame, they were melted in greater numbers than in case (a). Thus, a higher current intensity led to a decrease in pores and a more uniform deposition of the ceramic layer, [101, 102].

The microscopic image of the cross-section of the polymer composite coated with a ceramic layer is shown in Figure 4. Figure 4(a) highlights the existence of cracks in the substrate and Figure 4(b) indicates the poor adhesion between the coating and the substrate. This defect probably occurred due to the fact that the current for coating (270A) was higher than that of the coating links (180A). It is known that the plasma jet velocity and thermal energy increase with increasing current, which causes an increase in particle velocity and temperature, respectively. With higher current intensity, the temperature of airborne particles first increases up to 500A and then decreases, [103]. Aluminum oxide particles sprayed with a higher current intensity had a higher temperature. Cracks and delaminations will certainly reduce the adhesion strength of the coatings. The black arrows indicate on the left side of figure 4 the cracks in the polymer and those on the right side indicate the lack of adhesion between the coating and the substrate.

Table 2. Study from the technical literature regarding the coating of polymer/composite materials with a polymer matrix

Substrate	Coating material	The spray method *	Analysis	Reference
PA 66 (thermoplastic)	Al	CS	structural analysis, analysis of the influence of deposition parameters in order to optimize them, roughness and porosity	[18]
Epoxy reinforced with carbon fibers (thermoset)- CFRP	Al	CS	the connection mechanism, volume resistivity determination, structural analysis	[59]
Polycarbonate Lexan	Al	CS	surface morphology, normalized deposition efficiency and deposition degree for different powder feed rates	[14]
PEEK – carbon fiber reinforced polymer (thermoplastic)	Al	CGDS	corrosion damage, adhesion of the deposited layer to the substrate and cross-sectional analysis of the sample	[60]
PE textile materials	Al	Flame Spraying and Wire Flame Plating	microstructure and electrical conductivity	[61, 62]
Epoxy reinforced with glass fibers (thermoset)	Al	Flame spraying	coating and electrical conductivity characteristics, XRD structural analysis, mechanical pressure testing	[63]
Polymer matrix composites (PMCs)	Al, Al_2O_3	APS	mechanical properties (adhesion strength, nanohardness) and microstructure (SEM, XRD)	[15]
Carbon Fiber Reinforced Polymer Matrix Composite (PMC)	Al, Al/Cu	Cold nitrogen spray system	microstructural analysis, microhardness and resistance of the bonds made by coating	[64]
Thermo-set polyimide (thermo-resistant material) reinforced with carbon fiber	Al, Zn, Cu, Ni_3Al/Al_2O_3	APS and electric arc spraying	coating adhesion study	[16]
PMC	Al- Al_2O_3	APS	analysis of the influence of process parameters on structure, adhesion and mechanical properties	[65]
PEEK450CA30	Al și Al/Cu	CS	study on the mechanism of creating bonds between the substrate and the coating layer	[64]
Composite based on polyamide and graphite fibers	Al_2O_3, NiCrAlY și a-SiN:H	Magnetron sputtering and MOCVD	analysis of deposit adhesion and oxidation resistance	[17]
Composite with polymer matrix	Al_2O_3 și SiO_2	CVD, Plasma spraying and micro-arc oxidation	microstructural analysis for different time periods	[66]
Epoxy polymer reinforced with carbon fibers	Al_2O_3	Plasma spraying and micro-arc oxidation	wear resistance, XRD, EDS, adhesion strength	[67]
PEEK450CA30 reinforced with carbon fibers	Al, Cu	CS	the bonding mechanism of coatings, structural analysis	[64]
PC/ABS, polyamide-6, polypropylene and a composite material based on glass fibers	Al, Cu, Sn	CS	polymer wear, study of how polymer substrates are affected by process parameters	[68]
PU (thermoset)	Al-12silicon (Cu intermediate layer)	Flame spraying	structural analysis, deposition efficiency	[69]
Composite with epoxy matrix reinforced with glass fibers (thermoset)	Al-12silicone	Flame spraying	thermal analysis, SEM	[70]
Glass fiber reinforced epoxy	Al-12silicone	Flame spraying	SEM, leakage behavior, determination of error propagation	[71]
Glass fiber reinforced epoxy	Al-12silicone	Flame spraying	tensile testing, electrical resistance	[72, 73]
PU (thermoset)	Al-12silicone	Flame spraying	mathematical modeling that was based on the approach of an ecological function, aiming at the predefinition of the temperature distribution in the polymer substrate during the deposition, mechanical analysis in dynamic regime, morphological analysis of the surface, electrical resistance, electrical conductivity, morphological characterization of the coating (XRD, hardness, SEM)	[74-77]

Thermoset PI reinforced with carbon fibers	Al, Zn, Cu, Ni_3Al/Al_2O_3	Arc spray and APS	adhesion strength	[16]
Composite with PI matrix	Al_2O_3, SiO_2	CVD, plasma spraying and micro-arc oxidation	different temperature ranges affect the coating microstructure and phase composition	[66]
CFPI	Al and Al/Cu	CS	coating mechanism analysis	[64]
PI reinforced with carbon fibers	Al_2O_3, NiCrAlY and a-SiN:H	metal-organic CVD and plasma enhanced CVD	coating adhesion and coating oxidation resistance	[17]
Polymer reinforced with carbon fibers	Cu	APS	the study of the adhesion of the deposited layer by tracking crack propagation and interlaminar rupture tests	[78]
PEEK reinforced with carbon fibers	Cu	CS	adhesion strength of the metal layer, electrical behavior of the coating	[79]
PVC (thermoplastic)	Cu, Sn	CS	shear bond strength, Vickers hardness, electrical resistivity, structural analysis (SEM, XRD, EDX, FIB).	[80]
Thermoplastics: Nylon 6, HDPE Polyurethane	Cu	CS	the antifouling character of the coating.	[81, 82]
CFRP	Cu	APS	rezistența adeziunii	[78]
PVC (thermoplastic) and epoxy (thermoset)	Cu, Sn	CS	deposition efficiency, surface morphological analysi	[83]
PU, HDPE , PP, nylon 6, PTFE și PC	Cu	CS	effects of spray temperature and spray speed on particle penetration, weight gain and deformation of coated samples, tribological properties (coefficient of roughness and self-friction), electrical resistance.	[84]
Epoxy reinforced with carbon fibers	Cu	Plasma spraying	XPS, percentage of bonds created, topography of treated and untreated samples (thermal, chemical and mechanical), adhesion strength, SEM, contact angle, surface energy	[85]
PA6	Cu	CS	adhesion strength, electrical conductivity, oxygen content and microstructure (SEM)	[86]
CFPI	Cr_3C_2-NiCr,WC-Co	APS	ability to withstand wear and thermal shock	[15]
Polyamide matrix composite, quartz fiber reinforced (QFPI) and CFPI	CoNiCrAlY/8YSZ, Zn/8YSZ, Al/8YSZ	APS and HVOF	improving thermal shock and antioxidation resistance for different temperature ranges	[87-91]
epoxy composite reinforced with carbon fibers in a single direction	NiCrAlY and NiCr	Flame spraying	electrical characterization, Joule heating tests, SEM, EDX, fiber volume in the composite substrate	[92]
PEK (thermoplastic)	Ti	Cold gas spray	Micro-Raman analysis, XRD	[93]
Heat-set polyimide reinforced with graphite fibers	Zn/Ni-Cr-B-Si	Arc spray	Increasing the resistance of the bonds formed to shear and thermal fatigue	[7]
Epoxy tapes reinforced with carbon fiber and epoxy tapes reinforced with carbon fiber (Thermoset)	Zn (intermediate layer of Cu)	P-GDS	structural analysis (reduced porosity) and micro-hardness	[94]
QFPI and CFPI	Zn/8YSZ, CoNiCrAlY/8YSZ, Al/8YSZ	HVOF and APS	shock and antioxidation resistance (for different temperature ranges)	[87, 89-91, 95]
Composite with polyamide matrix	$Zr_{0.75}Ce_{0.25}O_2$/fosfat	The sol-gel/sealant treatment process	improving thermal oxidation and resistance to thermal ablation	[96]
QFPI	$Zr_{0.75}Ce_{0.25}O_2$/fosfat	Sol-gel	thermal oxidation and ablation resistance improved	[96]
T650-35/PMR-15	PMR-II /WC-Co	HVOF and flame spraying	determining the strength of the bonds created by coating	[97]
T650-35/PMR-15	PMR-II+WC-Co/Zinc /WC-Co	HVOF and flame spraying	improving wear resistance and anti-oxidation	[98, 99]
T650-35/PMR-15	PMR-II /WC-Co and PMR-II+WC-Co/Zinc /WC-Co	HVOF and flame spraying	bond strength, wear resistance and anti-oxidation	[97-99]

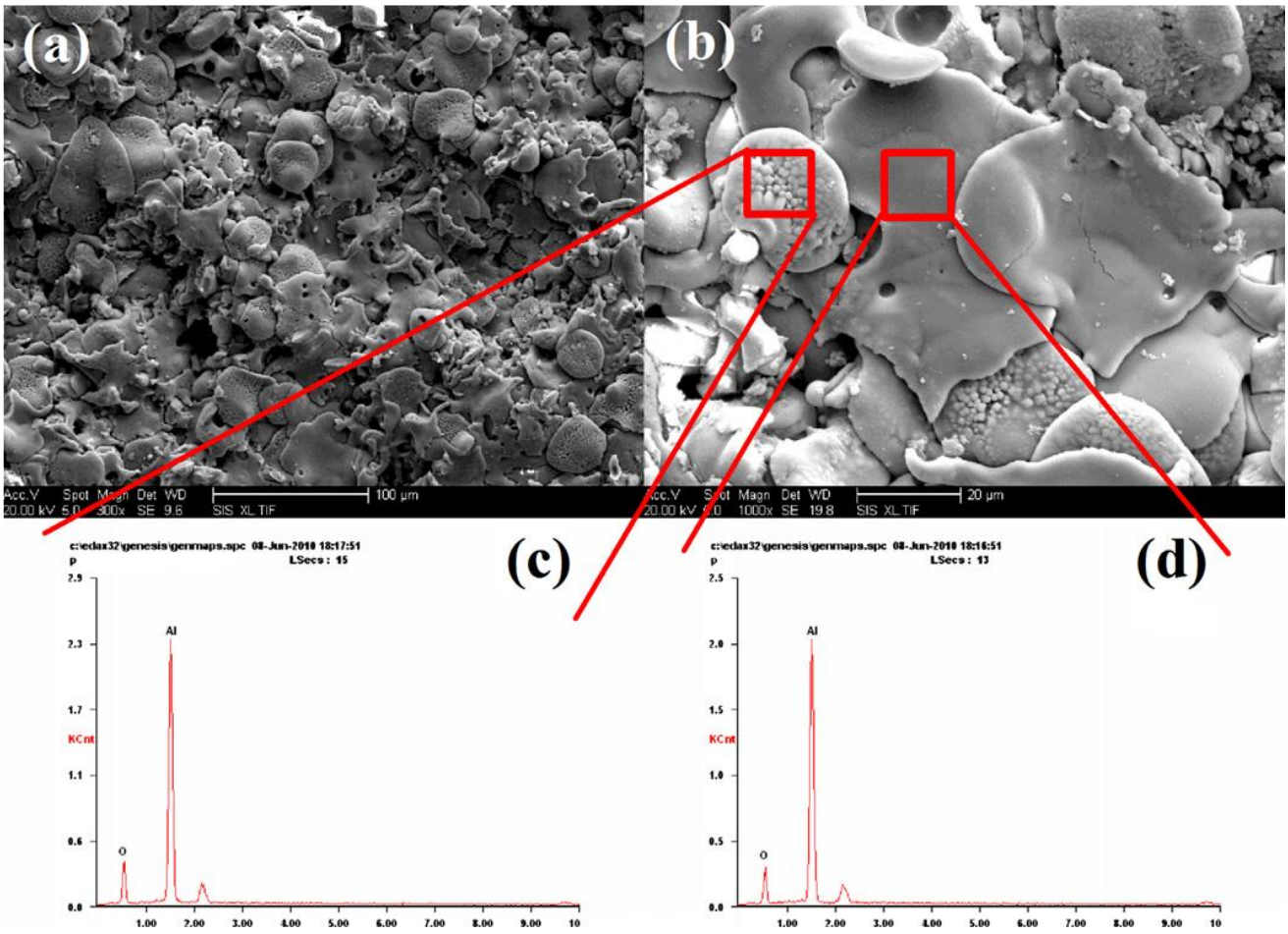


Fig. 2. Surface morphology of the ceramic coating: at reduced magnitude (a); at high magnitude (b); EDX analysis on porous splat (c) and EDX analysis on smooth splat (d), [75]

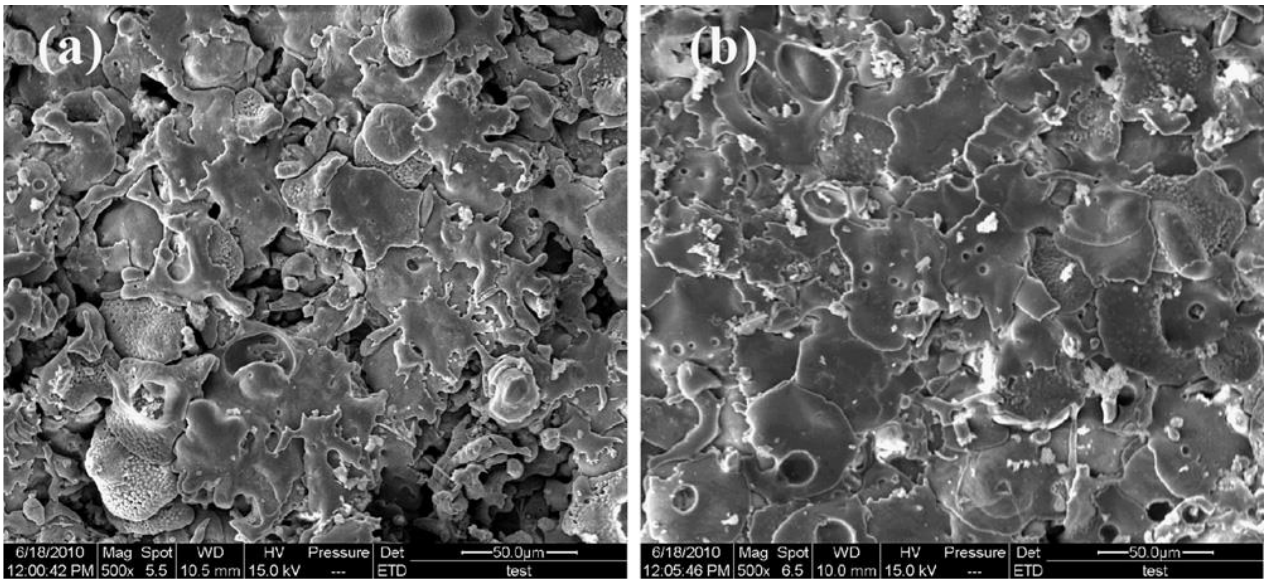


Fig. 3. Surface morphology of samples obtained by sputtering ceramic nanoparticles with varying current intensity: (a) 300 A and (b) 360 A, [65]

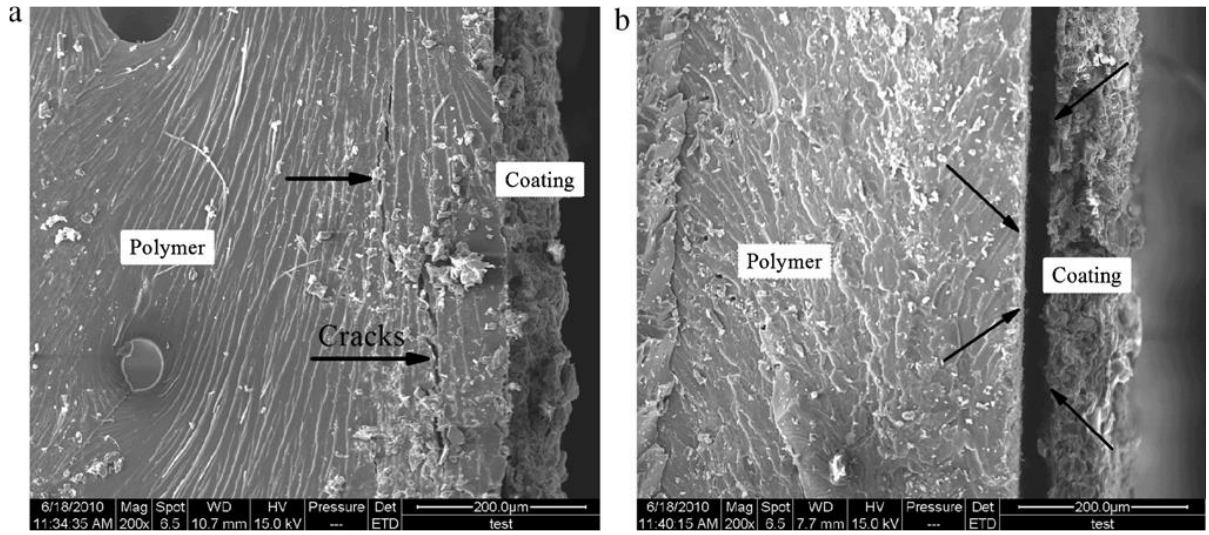


Fig. 4. Sectional view of samples coated using different sputtering parameters: (a) 150A – current intensity - coating links, 270A – sputtering current intensity, (b) 180A – current intensity - coating links, 270A – sputtering current intensity, [65].

Figure 5 shows the XRD patterns of the deposited Al_2O_3 layer, which suggests that the coating is composed of α-Al_2O_3, γ-Al_2O_3 and aluminum. It is known from the specialized literature that γ-Al_2O_3 is one of the intermediate phases formed when alumina is melted in the plasma jet, [99]. On cooling from the alumina melting temperature, γ -Al_2O_3 nucleates first over α -Al_2O_3; therefore, γ -Al_2O_3 commonly occurs in plasma thermally sprayed alumina coatings. The presence of aluminum is due to the lack of top layer coverage. To prevent thermal degradation of PMC, the process parameters were set to meet the following requirements: long spray distance, short spray time, and relatively low spray current intensity.

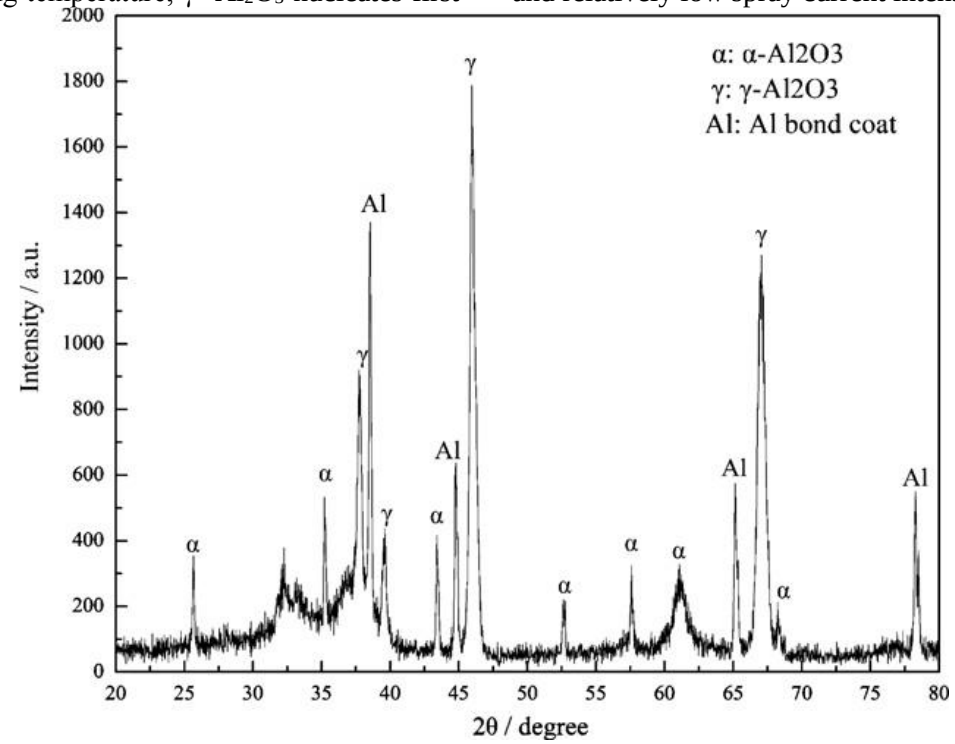


Fig. 5. XRD analysis of aluminum oxide ceramic coating, [65]

Shear strength of adhesion (between layer and substrate).

Figure 6 shows the shear strength of the topcoats. For the coated samples using a current of 330A and 360A respectively, the adhesion strength is too weak and could not be tested. It is observed that the shear adhesion strength is the highest – 1.13 MPa for the T3 sample with a spraying distance of 170mm, current for the upper layer of 270A and current for the bonding layer of 180A, and the lowest – 0.21 MPa for the T5 sample with spraying distance of 190mm, current for the upper layer of 270A and of the intermediate layer of 180A. The adhesion/shear adhesion strength of the top layers dropped below 1.2 MPa, due to thermal damage during the spraying process.

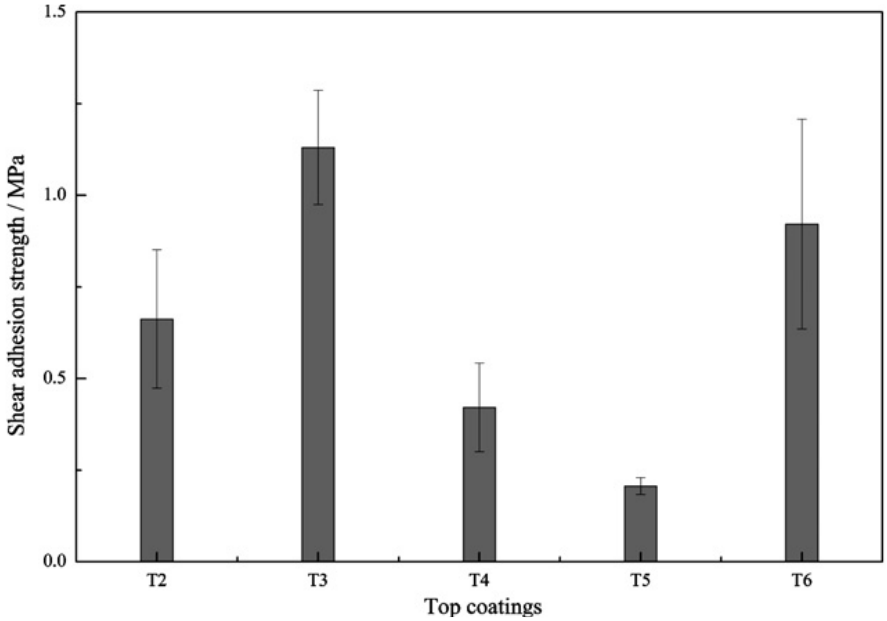


Fig. 6. Shear bond strength for aluminum oxide top layer, [65]

Nanoindentation

Nanoindentation was tested on the surface of samples with sputtering current of 270A, 300A and 330A respectively, interlayer/bond layer and PMC. The results are shown in Figure 7. First, the nanohardness of the Al_2O_3 top layer is much higher than the nanohardness of the Al bonding layer and the PMC substrate, which suggests that APS technology can be used to increase the surface hardness. However, the hardness obtained for the deposited coatings is much lower than the nanohardness of the alumina layer, [42], which has an average value of approximately 0.46 GPa. The reason for the reduction in nanohardness of the coating is that the nanohardness was achieved on a system containing a hard coating and a soft substrate. The very soft substrate (Young's modulus about 1.7 GPa) can strongly affect the result of the nanoindentation test, [104-106].

3.2. Coating with neodymium zirconate ($Nd_2Zr_2O_7$)

The present study used Al as an intermediate layer between the top layer of $Nd_2Zr_2O_7$ and the polymer substrate (polymer matrix composite reinforced with quartz fibers and containing (30-35)% polyamide resin, [107].

Morphology and structure

After layer deposition, the phase compositions of the powders and the deposited layers (top and middle) are compared in Figure 7. As can be seen from this diffractogram, the diffraction peaks at (111), (222), (220), (311) and (222) with reflections of pure Al, well indexed for Al powders at 2 = 38.5°, 44.7°, 65.1°, 78.2°, and 82.5° (JCPDS 65-2869). There are no noticeable peaks for other phases in XRD pattern of the Al coating, thus highlighting the fact that during the plasma sputtering procedure, there doesn't seem to be any oxidation of Al.

Relatively, the peak corresponding to the Al coating has a small change compared to that of the Al micro-particles, being mostly ascribed to the residual stress composed of cooling stresses and compressive stresses after coating process. Typically, compressive stresses derive mainly from the contraction of individual sprays when they have cooled to the temperature of the substrate (cold/unheated). The cooling stresses resulted from a mismatch in the thermal expansion rates of the substrate (polymer) and the deposited material/powder when they were wholly cooled (room temperature), [65]. As seen in Figure 7, the Nd_2Zr_2O7 coating's diffraction peaks match those of the $Nd_2Zr_2O_7$ powder, demonstrating the material's outstanding phase stability, in the extremely high temperature plasma flame. The shape of the diffraction peaks of the powders and the coating, sharp and narrow, suggest good crystallinity, but the coatings' diffraction peak intensities are lower than those from the powders', possibly because the amorphous phase has formed in the coatings during the annealing process, recrystallization, [107]. The typical morphological structure of the substrate and the deposited top layer are shown in Figure 8. As can be seen in Figures 8(a) and 8(b), the substrate surface resins are ground with abrasive paper to remove them and reveal the strands, in while the effective surface roughness, the surface of the substrate is (2.63±0.098) μm. In general, the plasma flame has an extremely high temperature, while the raw materials are exposed in the perimeter of the flame for a very short time, then they solidify quickly on the substrate (solidification rate greater than 106 K/s), [108]. The raw material particles display various melting states as a result during thermal spraying. As observed in Figure 8(c) and 8(e), coexistence of unmelted, partially melted, and fully melted particles led to the creation of both rough and smooth areas in the coating. The coarse

portions of the Al layer and the $Nd_2Zr_2O_7$ layer are primarily made up of unmelted or partially melted particles, and the random stacking of these particles during cooling results in the production of non-uniform coating surface morphologies after cooling. The rough and uneven surface of the deposited Al layer may be beneficial to create a mechanical connection between the $Nd_2Z_{r2}O_7$ layer and the Al layer, the distribution of fully melted Al particles is primarily responsible for the smooth area in the Al layer, Figure 8(d). However, The distribution of lamellae/splats produced by fully melted Nd2Zr2O7 particles is caused by the higher melting point of Nd2Zr2O7 compared to Al. The development of tiny fissures in a smooth area can be attributed to the shrinkage of the molten particles during the cooling process Figure 8(f), which released the stresses in the coating during thermal cycling, [108].

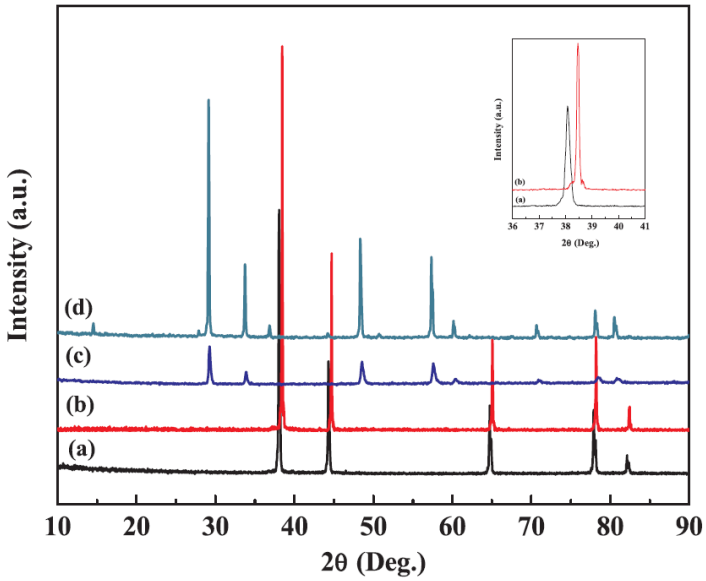


Fig. 7. Diffractometric analysis of powders and coatings involved in the study, [107]: Al coating (a), Al powder (b), $Nd_2Z_{r2}O_7$ coating (c) and $Nd_2Z_{r2}O_7$ powder (d).

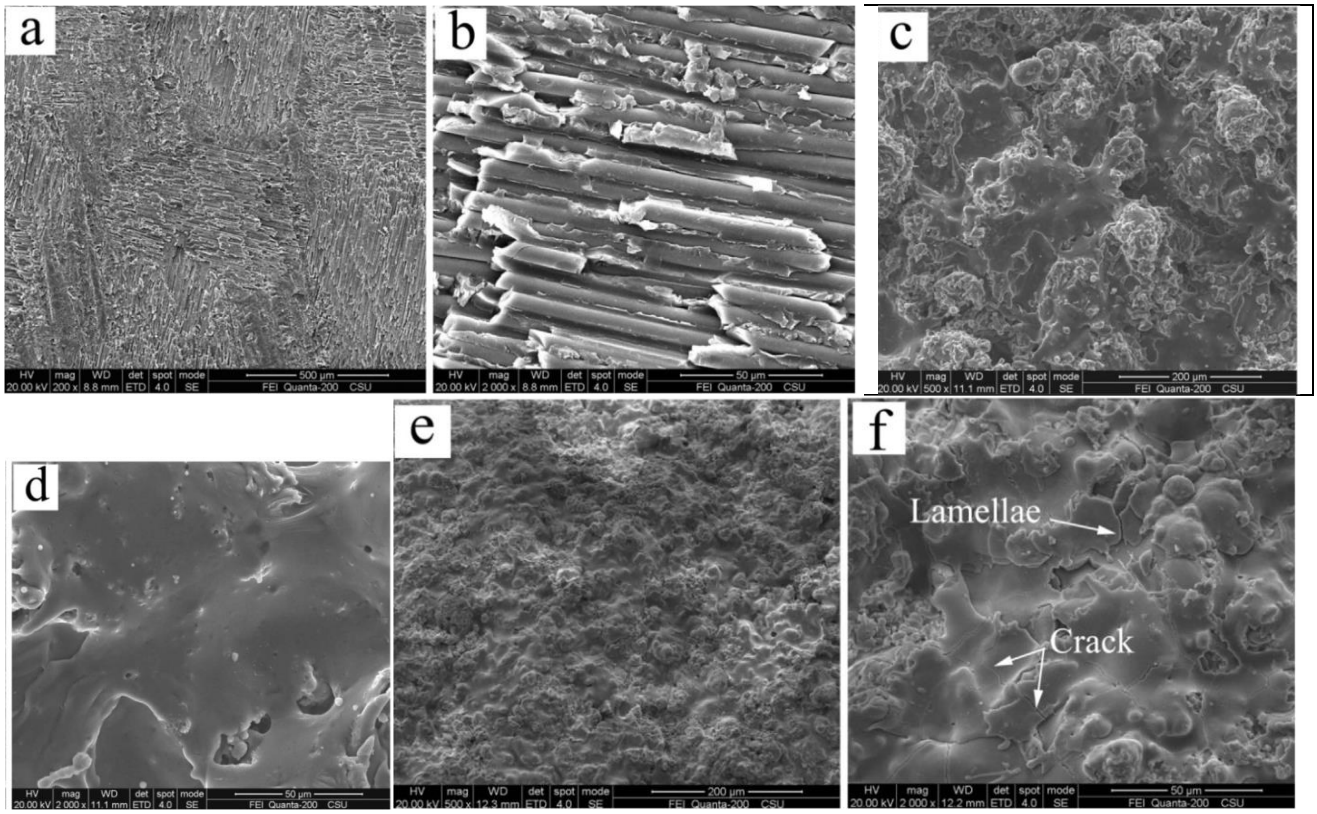


Fig. 8. Typical surface morphologies of the substrate, interlayer and top layer: substrate (a, b), aluminum intermediate state (c, d), and Nd2Zr2O7 coating (e, f) [107].

To further investigate the adhesion between the coating layer and the deposited interlayer, the microstructures of the coatings' cross-sections at various thicknesses for Al and $Nd_2Zr_2O_7$ layers were compared in Figure 9 and respectively Figure 10. Because the intermediate layer's melting point is lower (933 K) than the higher layer's melting point (2573 K) for all coating materials, the interior Al layer is significantly dense than the upper Nd2Zr2O7 layer [8]. At the same time, the contact between both the Al coating and the substrate is visible, and there are no obvious flaws there, which leads to the conclusion that the molten Al particles do not degrade or damage the surface of the polymer substrate during plasma spraying. However, due to the rapid cooling (caused by the deposition on the cold surface of the sample) of the $Nd_2Zr_2O_7$ particles, the upper layer shows obvious defects in the form of holes or pores, which, according to the literature, are characteristic of ceramic coating by APS. The typical microstructures obtained by depositing two layers (one intermediate and one upper) are favorable for minimizing heat conduction and continuously improving the thermal protection capability of the coating.

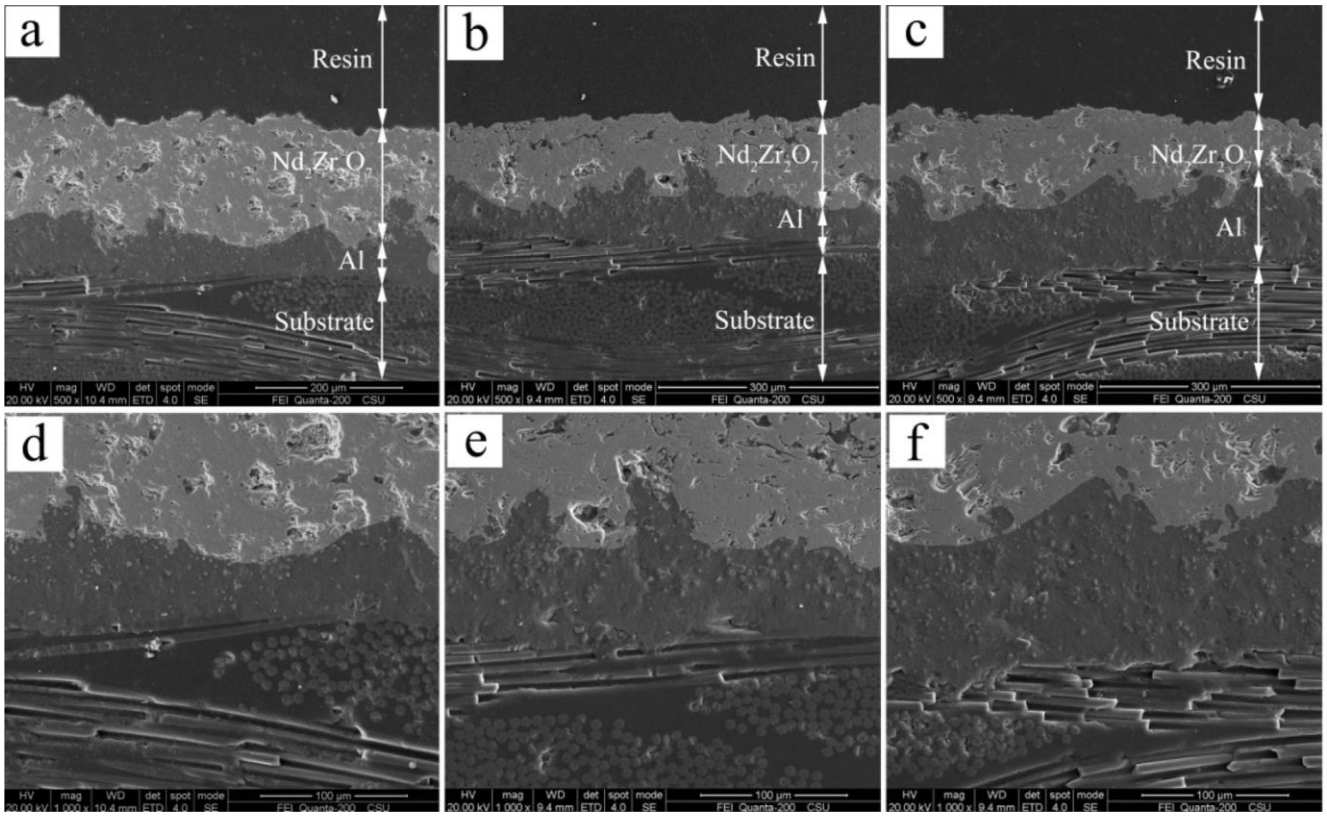
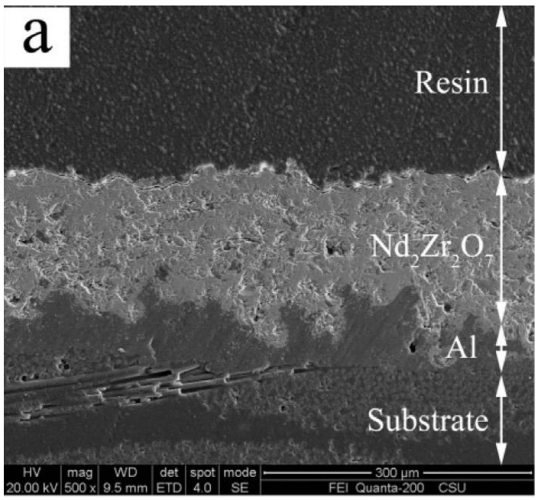


Fig. 9. Standard microstructures for coatings with various Al: (a, d) A45N100, (b, e) A60N100 and (c, f) A97N100, [107].

The average microhardness of the substrate, Al intermediate layer and $Nd_2Zr_2O_7$ upper layer showed the following values: 38.4 HV - substrate, 43.5 HV - Al intermediate layer and 363.4 HV - ceramic layer, respectively (Figure 11). According to Figure 11It is interesting to note that the $Nd_2Zr_2O_7$ layer has a microhardness that is significantly higher than both the substrate and the Al layer, indicating that the deposition of the $Nd_2Zr_2O_7$ ceramic top layer may be advantageous for increasing the microhardness of the PMC surface.



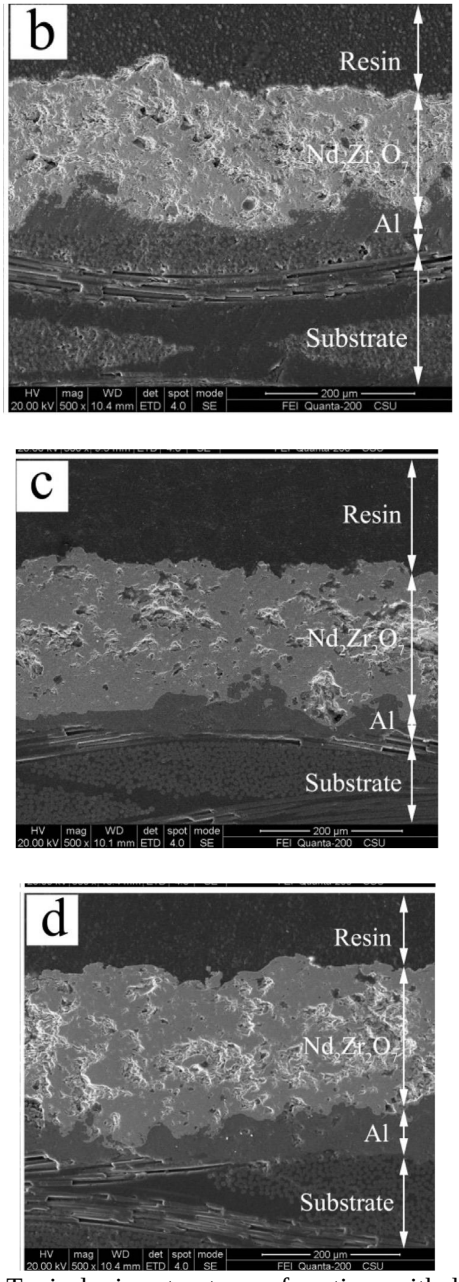


Fig. 10. Typical microstructures of coatings with different $Nd_2Zr_2O_7$ layer thicknesses: (a) 45 µm Al state and 100 µm $Nd_2Zr_2O_7$ layer, (b) 45 µm Al layer and 160 µm $Nd_2Zr_2O_7$ layer, (c) 45 µm Al layer and 200 µm $Nd_2Zr_2O_7$ layer, (d) 45 µm Al layer and 225 µm $Nd_2Zr_2O_7$ layer, [107].

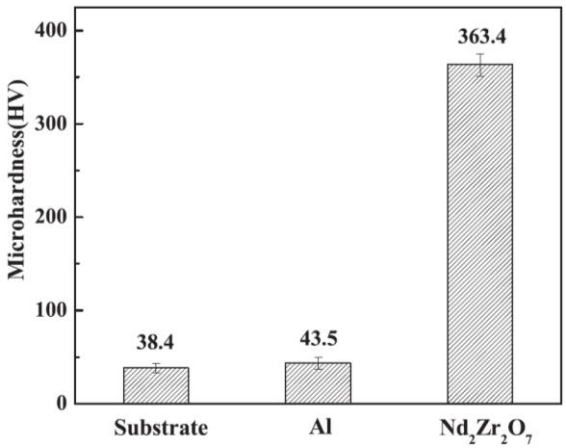


Fig. 11. Microhardness of the substrate and the two deposited layers (Al and $Nd_2Zr_2O_7$), [108].

4. CONCLUSIONS

XRD analysis revealed that the coatings have a crystalline structure (with specific crystallization peaks of pure aluminum), and the sputtering parameters had no effect on the phase composition of the coatings. The highest layer shear strength was 5.21 MPa – sample sprayed with a current of 180A and a spray distance of 190 mm. In order to obtain Al_2O_3 top layers with higher adhesion strength, the possibility of using another polymer with higher thermal resistance was considered, and it was also considered that cooling the substrate during sputtering would lead to better results. In conclusion, the coating of the composite polymer with aluminum oxide ceramic state favored the increase of the surface hardness of the tested/analyzed benchmarks.

Following the results presented regarding the coating of the polymer matrix composite with $Nd_2Zr_2O_7$ ceramic layer, the following conclusions can be drawn:

- the XRD analysis revealed the crystalline character of the deposited layers (intermediate layer of Al and upper layer of $Nd_2Zr_2O_7$);
- the structural analysis undertaken on the coated samples (surface and cross-section) made it possible to identify some defects (pores, cracks, lack of adhesion) that are specific to coatings with ceramic layers, but they can be minimized by carefully controlling the process parameters;
- $Nd_2Zr_2O_7$ layer has a significantly higher microhardness than the substrate and the Al layer, highlighting the possibility of improving the PMC surface.

REFERENCESS

1. Martin, J.E., Stevens, T., Bellen, G.E., King, L.W., Hylko, J.M., (1990). *Tracer study of polyacrylate polymer in a waste-water plant*, Appl Radiat. Isot., 41, 1165–1172.
2. Hoff, S.M., (1995). *Applying advanced materials to turboshaft engines*, Aerospace Eng., 15, 27–30.
3. Lampe, T., Eisenberg, S., Cabeo, E.R., (2003). *Plasma surface engineering in the automotive industry—trends and future prospectives*, Surf. Coat. Technol., 174, 1–7.
4. Wang, Y., Jiang, S., Wang, M.D., Wang, S.H., Xiao, T.D., Strutt, P.R., (2000). *Abrasive wear characteristics of plasma sprayed nanostructured alumina/titania coatings*, Wear, 237, 176–185.
5. Choi, J.W., Hwang, G.H., Han, W.K., Lee, W.H., Kang, S.G., (2007). *Effect of Cu on the surface hardness of Ni–B coating for the strengthening of the Cu surfac*e, Met. Mater. Int., 13, 403–409.

6. Choe, H.C., Ko, Y.M., (2006). *Interface activation and surface characteristics of Ti/TiN/HA coated sintered stainless steels*, Met. Mater. Int., 12, 31–37.
7. Liu, A.G., Guo, M.H., Zhao, M.H., Ma, H., Hu, S.H., (2006). *Arc sprayed erosion-resistant coating for carbon fiber reinforced polymer matrix composite substrates*, Surf. Coat. Technol., 200, 3073–3077.
8. Petrovicova, E., Schadler, L.S., (2002). *Thermal spraying of polymers*, Int. Mater. Rev., 47, 169–190, https://doi.org/10.1179/095066002225006566.
9. Gonzalez, R., Ashrafizadeh, H., Lopera, A., Mertiny, P., McDonald, A., (2016). *A review of thermal spray metallization of polymer-based structures*, J. Therm. Spray. Technol., 25, 897–919.
10. Shacham-Diamand, Y., Osaka, T., Okinaka, Y., Sugiyama, A., Dubin, V., (2015). *30 Years of electroless plating for semiconductor and polymer micro-system*s, Microelectron. Eng., 132, 35–45.
11. Ghosh, S., (2019). *Electroless copper deposition: a critical review*, Thin Solid Films, 669, 641–658.
12. Mavukkandy, M.O., McBride, S.A., Warsinger, D.M., Dizge, N., Hasan, S.W., Arafat, H. A., (2020). *Thin film deposition techniques for polymeric membranes – a r*eview, J. Memb. Sci., 610, 118258.
13. Ferreira, A.A., Silva, F.J.G., Pinto, A.G., Sousa, V.F.C., (2021). *Characterization of thin chromium coatings produced by PVD sputtering for optical applications*, Coatings, 11, 1–20.
14. Ye, H., Wang, J., (2014). *Preparation of Aluminum Coating on Lexan by Cold Spray*, Mater. Lett., 137, 21-24.
15. Meador, M., (2001). *Coatings for high temperature polymer composites*, in: Proceedings of the 46th International SAMPE Symposium and Exhibition, p. 572.
16. Liu, A., Guo, M., Gao, J., (2006). *Influence of Bond Coat on Shear Adhesion Strength of Erosion and Thermal Resistant Coating for Carbon Fiber Reinforced Thermosetting Polyimide*, Surf. Coat. Technol., 201, 2696.
17. Harding, D.R., Sutter, J.K., Schuerman, M.A., Crane, E.A., (1994). *Oxidation protective barrier coatings for high temperature polymer matrix Composites*, J. Mater. Res., 9, 1583.
18. Giraud, D., Borit, F., Guipont, V., Jeandin, M., Malhaire, J.M., (2012). *Metallization of a polymer Using Cold Spray: Application to Aluminum Coating of Polyamide 66*, International Thermal Spray Conference 2012 (Houston, TX), pp. 265-270.
19. Lu, Z., Myoung, S.W., Kim, E.H., Lee, J., Hand Jung, Y.G., (2014). *Microstructure Evolution and Thermal Durability with Coating Thickness in APS Thermal Barrier Coatings*, Materials Today: Proceedings, 1(1), 35-43.
20. Matikainen, V., Bolelli, G., Koivuluoto, H., Sassatelli, P., Lusvarghi, L., Vuoristo, P., (2017). *Sliding wear behaviour of HVOF and HVAF sprayed Cr3C2-based coating*, Wear, 388-389, 0–1.
21. Suarez, M., Bellayer, S., Traisnel, M., Gonzalez, W., Chicot, D., Lesage, J., Puchi-Cabrera, E. S., Staia, M.H., (2008). *Corrosion behavior of Cr_3C_2–NiCr vacuum plasma sprayed coatings*, Surf. Coat. Technol., 202(18), 4566–4571.
22. Gariboldi, E., Rovatti, L., Lecis, N., Mondora, L., Mondora, G.A., (2016). *Tribological and mechanical behaviour of Cr3C2–NiCr thermally sprayed coatings after prolonged aging*, Surf. Coatings Technol., 305. 83–92.
23. Tsui, Y.C., Clyne, T.W., (1997). *An analytical model for predicting residual stresses in progressively deposited coatings Part 2: Cylindrical geo*metry, Thin Solid Films, 306, 23–33.
24. Rajkovic, A., Uyttendaele, M., Deley, W., Van Soom, A., Rijsselaere, T., Debevere, J., (2006). *Dynamics of boar semen motility inhibition as a semi-quantitative measurement of Bacillus cereus emetic toxin (Cereulide)*, J Microbiol Methods, 65, 525–534.
25. Divine. S., Chun-Wei, Y., Ian, L., (2018). *Mechanical Durability of Engineered Superhydrophobic Surfaces for Anti-Corrosion*, Coatings, 8, 162.
26. Thakur, V., Kessler, M., (2015). *Self-Healing Polymer Nanocomposite Materials: A Review*, Polymer, 69, 369–383.
27. Ulaeto, S., Rajan, R., Pancrecious, J., Rajan, T., Pai, B., (2017). *Developments in Smart Anticorrosive Coatings with Multifunctional Characteristics*, Prog. Org. Coat., 111, 294–314.
28. Asri, N., Husaini, T., Sulong, A., Majlan, E., Daud, W., (2017). *Coating of Stainless Steel and Titanium Bipolar Plates for Anticorrosion In PEMFC: A Review*, Int. J. Hydrogen Energy, 42, 9135–9148.
29. Gao, X., Liu, H., Cheng, F., Chen, Y., (2016). *Thermoresponsive Polyaniline Nanoparticles: Preparation, Characterization, and Their Potential Application in Waterborne Anticorrosion Coatings*, Chem. Eng. J., 283, 682–691.
30. Sorensen, P., Kiil, S., Dam-Johansen, K., Weinell, C., (2009). *Anticorrosive Coatings: A Review*, J. Coat. Technol. Res., 6, 135–176.
31. Zheludkevich, M., Shchukin, D., Yasakau, K., Möhwald, H., Ferreira, M., (2007). *Anticorrosion Coatings with Self-Healing Effect Based on Nanocontainers Impregnated with Corrosion Inhibitor*, Chem. Mater., 19, 402–411.
32. Ausanio, G., Hison, C.L., Iannotti, V., Lanotte, L., Lanotte, L., (2011). *Magneto-piezoresistance in elastomagnetic composites*, J. Appl. Phys., 110, 063903.
33. Dumitrescu, A., Lisa, G., Iordan, A., Tudorache, F., Petrila, I., Borhan, A., Palamaru, M., Mihailescu, C., Rocha-Santos, T.A., (2014). *Sensors and biosensors based on magnetic nanoparticles*, TrAC Trends Anal. Chem., 62, 28–36.

34. Freitas, P., Ferreira, R., Cardoso, S., Cardoso, F., (2007). *Magnetoresistive sensors*, J. Phys. Condens. Matter, 19, 165221.
35. Mocanu, Z., Airimioaei, M., Ciomaga, C., Curecheriu, L., Tudorache, F., Tascu, S., Iordan, A., Palamaru, N., Mitoseriu, L., (2014). *Investigation of the functional properties of MgxNi1-xFe2O4 ceramics*, J. Mater. Sci., 49, 3276–3286.
36. Leontie, L., Munteanu, C., (2015). *Ni ferrite highly organized as humidity sensors*, Mater. Chem. Phys., 156, 170–179.
37. Mohr, R., Kratz, K., Weigel, T., Lucka-Gabor, M., Moneke, M., Lendlein, A., (2006). *Initiation of shape-memory effect by inductive heating of magnetic nanoparticles in thermoplastic polymers*, Proc. Nat. Acad. Sci. USA, 103, 3540–3545.
38. Schmidt, A.M., (2006). *Electromagnetic activation of shape memory polymer networks containing magnetic nanoparticles*, Macromol. Rapid Commun, 27, 1168–1172.
39. Pankhurst, Q.A., Connolly, J., Jones, S., Dobson, J., (2003). *Applications of magnetic nanoparticles in biomedicine*, J. Phys. D Appl. Phys., 36, R167.
40. Berry, C.C., Curtis, A.S., (2003). *Functionalisation of magnetic nanoparticles for applications in biomedicine*, J. Phys. D Appl. Phys., 36, R198.
41. Liu, X., Li, B., Geng, D., Cui, W., Yang, F., Xie, Z., Kang, D., Zhang, Z., (2009). (*Fe, Ni)/C nanocapsules for electromagnetic-wave-absorber in the whole Ku-band*, Carbon, 47, 470–474.
42. Wu, N., Liu, X., Zhao, C., Cui, C., Xia, A., (2016). *Effects of particle size on the magnetic and microwave absorption properties of carbon-coated nickel nanocapsules*, J. Alloys Compd., 656, 628–634.
43. Li, Y., Wang, J., Liu, R., Zhao, X., Wang, X., Zhang, X., Qin, G., (2017). *Dependence of gigahertz microwave absorption on the mass fraction of Co@C nanocapsules in composite*, J. Alloys Compd., 724, 1023–1029.
44. Fotovvati, B., Namdari, N., Dehghanghadikolaei, A., (2019). *On coating techniques for surface protection: a review*, J. Manuf. Mater. Process, 3, 22.
45. Available from: http://www.teandm.pt/aps_T_eng.htm, Accessed: 28/06/2020.
46. Kim, K., Kim, W., (2021). *Effect of Heat Treatment on Microstructure and Thermal Conductivity of Thermal Barrier Coating*, Materials, 14, 7801.
47. Salavati-Niasari, M., Davar, F., Mir, N., (2008). *Synthesis and characterization of metallic copper nanoparticles via thermal decomposition*, Polyhedron, 27(17), 3514–3518.
48. Safavi, M.S., Walsh, F.C., Surmeneva, M.A., Surmenev, R.A., Khalil- Allafi, J., (2021). *Electrodeposited Hydroxyapatite- Based Biocoatings: Recent Progress and Future Challenges*, Coatings, 11, 110.
49. Kulkarni, A., Frettlöh, V., (2018). *Simulation of CVD Process in a Reactor*, Excerpt from the Proceedings of the 2018 COMSOL Conference, Lausanne, pp. 1-6, https://www.comsol.com/paper/download/571561/kulkarni_paper.pdf.
50. Priyadarshini, B., Rama, M., Chetan, Vijayalakshmi, U., (2019). *Bioactive coating as a surface modification technique for biocompatible metallic implants: a review*, Journal of Asian Ceramic Societies, 7(4).
51. Musztyfaga-Staszuk, M., Czupryński, A., Kciuk, M., (2018). *Investigation of mechanical and anti-corrosion properties of flame sprayed coatings*, Advances in materials science, 18, 4(58).
52. Available from: https://www.mecpl.com/products/coating-equipments/cold-spray/, Accessed:28/06/2020.
53. Ma, Y., Han, J., Wang, M., Chen, X., Jia, S., (2018). *Electrophoretic deposition of graphene-based materials: A review of materials and their applications*, J. Mater., 4, 108–120.
54. Besra, L., Liu, M., (2007). *A review on fundamentals and applications of electrophoretic deposition (EPD)*, Prog. Mater. Sci., 52, 1–61.
55. Melentiev, R., Yu, N., Lubineau, G., (2021). *Polymer metallization via cold spray additive manufacturing: A review of process control, coating qualities, and prospective applications*, Additive Manufacturing, 48, 102459.
56. Tai, C.Y., Tai, C.-T., Chang, M.-H., Liu, H.-S., (2007). *Synthesis of Magnesium Hydroxide and Oxide Nanoparticles Using a Spinning Disk Reactor*, Industrial & Engineering Chemistry Research, 46(17), 5536–5541.
57. Sigmund, W., Yuh, J., Park, H., Maneeratana, V., Pyrgiotakis, G., Daga, A., et al., (2006). *Processing and structure relationships in electrospinning of ceramic fiber systems*, J. Am. Ceram. Soc., 89, 395-407.
58. Thomas, S., Harshita, B.S.P., Mishra, P., Talegaonkar, S., (2015). *Ceramic nanoparticles: fabrication methods and applications in drug delivery*, Curr. Pharm. Des., 21, 6165-6188.
59. Affi, J., Okazaki, H., Yamada, M., Fukumoto, M., (2011). *Fabrication of Aluminum Coating onto CFRP Substrate by Cold Spray*, Mater. Trans., 52(9), 1759-1763.
60. Sturgeon, A., Dunn, B., Celotto, S., O'Neill, B., (2006). *Cold Sprayed Coatings for Polymer Composite Substrates*, 10th International Symposium on Materials in a Space Environment and The 8th International Conference on Protection of Materials and Structures in a Space Environment (Collioure, Languedoc-Roussillon), pp. 616-1-616-6.

61. Voyer, J., Schulz, P., Schreiber, M., (2008). *Conducting Flame-Sprayed Al Coatings on Textile Fabrics*, J. Therm. Spray Technol., 17(4), 583-588.
62. Voyer, J., Schulz, P., Schreiber, M., (2008). *Electrically Conductive Flame Sprayed Aluminum Coatings on Textile Substrates*, International Thermal Spray Conference 2008, (Maastricht, Limburg), 818-823.
63. Huonnic, N., Abdelghani, M., Mertiny, P., McDonald, A., (2010). *Deposition and Characterization of Flame-Sprayed Aluminum on Cured Glass and Basalt Fiber-Reinforced Epoxy Tubes*, Surf. Coat. Technol., 205(3), 867-873.
64. Zhou, X.L., Chen, A.F., Liu, J.C., Wu, X.K., Zhang, J.S., (2011). *Preparation of metallic coatings on polymer matrix composites by cold spray*, Surface and Coatings Technology, 206(1), 132-136.
65. Sun, G., He, X., Jiang, J., Yue, S., (2011). *Parametric study of Al and Al_2O_3 ceramic coatings deposited by air plasma spray onto polymer substrate*, Appl. Surf. Sci., 257, 7864.
66. Gulino, D.A., (1994). *Oxygen barrier coatings for enhanced stability of polyimide composites at elevated temperatures*, NASA Cooperative Agreement NCC3-194 report, NASACR-195904.
67. Sun, G., He, X., Jiang, J., Sun, Y., Zhong, Y., (2013). *A Study on the Deposition of Al2O3 Coatings on Polymer Substrates by a Plasma Spray/Micro-Arc Oxidation Two-Step Method*, J. Therm. Spray Technol., 22(1), 27-35.
68. Lupoi, R., O'Neill, W., (2010). *Deposition of Metallic Coatings on Polymer Surfaces Using Cold Spray*, Surf. Coat. Technol., 205(7), 2167-2173.
69. Boyer, H., McDonald, A., Mertiny, P., (2012). *Flame Spray Deposition of Electrically Conductive Traces on Polymer Substrates for System Integrated Composite Structures*, Composites, Las Vegas, NV, 1-6.
70. Therrien, D.S., McDonald, A.G., Mertiny, P., (2012). *Temperature Measurements of Polymer Composite Flat Plates Coated with Aluminum-12silicon*, International Thermal Spray Conference 2012 (Houston, TX), pp. 1-6.
71. Gonzalez, R., McDonald, A., Mertiny, P., (2013). *Effect of Flame-Sprayed Al-12Si Coatings on the Failure Behaviour of Pressurized Fibre-Reinforced Composite Tubes*, Polym. Test., 32(8), 1522-1528.
72. Gonzalez, R., McDonald, A.G., Mertiny, P., (2014). *Damage Detection Method for Fiber-Reinforced Polymer Composites Using Al-12Si Flame-Sprayed Coatings*, SAMPE Seattle 2014 Conference, (Seattle, WA), pp. 4056-1-4056-11.
73. Gonzalez, R., Mertiny, P., McDonald, A., (2015). *Damage Detection Framework for Fiber-Reinforced Polymer Composites Using Al-12Si Flame-Sprayed Coatings*, Canadian International Conference on Composite Materials, (Edmonton, AB), pp. 1-8.
74. Ashrafizadeh, H., Mertiny, P., McDonald, A., (2014). *Determination of Temperature Distribution Within Polyurethane Substrates During Deposition of Flame-Sprayed Aluminum-12silicon Coatings Using Green's Function Modeling and Experiments*, Surf. Coat. Technol., 259, 625-636.
75. Ashrafizadeh, H., Mertiny, P., McDonald, A., (2015). *Evaluation of the Influence of Flame Spraying Parameters on Microstructure and Electrical Conductivity of Al-12Si Coatings Deposited on Polyurethane Substrates*, International Thermal Spray Conference 2015 (Long Beach, CA), pp. 370-376.
76. Ashrafizadeh, H., McDonald, A., Mertiny, P., (2016). *Deposition of Electrically Conductive Coatings on Castable Polyurethane Elastomers by the Flame Spraying Process*, J. Therm. Spray Technol., 25(3), 419-430.
77. Ashrafizadeh, H., Mertiny, P., McDonald, A., (2014). *Analytical and Numerical Determination of Transient Temperature Within a Polyurethane Substrate During a Flame Spraying Process*, The Canadian Society for Mechanical Engineering International Congress, Toronto, ON, pp. 1-6.
78. Beydon, R., Bernhart, G., Segui, Y., (2000). *Measurement of metallic coatings adhesion to fibre reinforced plastic materials*, Surf. Coat. Technol., 126, 2000, 39–47.
79. Bortolussi, V., Borit, F., Chesnaud, A., Jeandin, M., Faessel, M., et al, (2016). *Cold spray of metal-polymer composite coatings onto carbon fiber-reinforced polymer (CFRP)*, International Thermal Spray Conference 2016 (ITSC 2016), DVS, Shanghai, China, 7, p. ffhal-01337696f.
80. Ganesan, A., Affi, J., Yamada, M., Fukumoto, M., (2012). *Cold spray of metal-polymer of Cold Sprayed Copper Coating on the PVC Polymer Substrate*, Surf. Coat. Technol., 207, 262-269.
81. Vucko, M.J., King, P.C., Poole, A.J., Carl, C., Jahedi, M.Z., de Nys, R., (2012). *Cold Spray Metal Embedment: An Innovative Antifouling Technology*, *Biofouling*, 28(3), 239-248.
82. Vucko, M.J., King, P.C., Poole, A.J., Jahedi, M.Z., de Nys, R., (2013). *Polyurethane Seismic Streamer Skins: An Application of Cold Spray Metal Embedment*, Biofouling, 29(1), 1-9.
83. Ganesan, A., Yamada, M., Fukumoto, M., (2013). *Cold Spray Coating Deposition Mechanism on the Thermoplastic and Thermosetting Polymer Substrates*, J. Therm. Spray Technol., 22(8), 1275-1282.
84. King, P.C., Poole, A.J., Horne, S., de Nys, R., Gulizia, S., Jahedi, M.Z., (2013). *Embedment of Copper Particles into Polymers by Cold Spray*, Surf. Coat. Technol., 216, 60-67.
85. Ganesan, A., Yamada, M., Fukumoto, M., (2013). *The Effect of CFRP Surface Treatment on the Splat Morphology and Coating Adhesion Strength*, International Thermal Spray Conference 2013 (Busan, Yeongnam), pp. 236-244.

86. Małachowska, A., Winnicki, M., Konat, L., Piwowarczyk, T., Pawłowski, L., Ambroziak, A., Stachowicz, M., (2017). *Possibility of spraying of copper coatings on polyamide 6 with low pressure cold spray method*, Surface & Coatings Technology, 318, 82–89.
87. Huang, W., Zhao, Y., Fan, X., Meng, X., Wang, Y., Cai, X., Cao, X., Wang, Z., (2013). *Effect of bond coats on thermal shock resistance of thermal barrier coatings deposited onto polymer matrix composites via air plasma spray process*, J. Therm. Spray. Technol., 22, 918.
88. Zhu, L., Huang, W., Cheng, H., Cao, X., (2014). *Thermal shock resistance of stabilized zirconia/metal coat on polymer matrix composites by thermal spraying process*, J. Therm. Spray. Technol., 23, 1312.
89. Huang, W., Fan, X., Zhao, Y., Zhou, X., Meng, X., Wang, Y., Zou, B., Cao, X., Wang, Z., (2012). *Fabrication of thermal barrier coatings onto polyimide matrix composites via air plasma spray process*, Surf. Coat. Technol., 207, 421.
90. Huang, W., Cheng, H., Zhang, C., Zhou, Y., Cao, X., (2015). *Thermal ablation of stabilized zirconia/metal coated polyimide matrix composites via plasma spray process*, Plasma Chem. Plasma Process., 35, 587.
91. Huang, W., Cheng, H., Zhou, Y., (2015). *Oxidation behavior of plasma-sprayed stabilized zirconia/Al coated polymer matrix composites*, RSC Adv. 5, 72331.
92. Lopera-Valle, A., McDonald, A., (2015). *Use of Flame-Sprayed Coatings as Heating Elements for Polymer-Based Composite Structures*, International Thermal Spray Conference 2015 (Long Beach, CA), pp. 1183-1190
93. Gardon, M., Latorre, A., Torrell, M., Dosta, S., Fernandez, J., Guilemany, J.M., (2013). *Cold Gas Spray Titanium Coatings onto a Biocompatible Polymer*, Mater. Lett., 106, 97-99.
94. Robitaille, F., Yandouzi, M., Hind, S., Jodoin, B., (2009). *Metallic Coating of Aerospace Carbon/Epoxy Composites by the Pulsed Gas Dynamic Spraying Process*, Surf. Coat. Technol., 203(19), 2954-2960.
95. Zhu, L., Huang, W., Cheng, H., Cao, X., (2014). *Thermal shock resistance of stabilized zirconia/ metal coat on polymer matrix composites by thermal spraying process*, J. Therm. Spray. Technol., 23, 1312.
96. Huang, W. Wang, Z., Xu, J., Fan, X., Wang, Y., Zou, B., Cao, X., (2013). *Novel thermal protection coating based on Zr0.75Ce0.25O2/phosphate duplex system for polyimide matrix composites fabricated via a combined sol-gel/sealing treatment process*, Corros. Sci., 74, 22.
97. Ivosevic, M., Knight, R., Kalidindi, S.R., Palmese, G.R., Sutter, J.K., (2005). *Adhesive/cohesive properties of thermally sprayed functionally graded coatings for polymer matrix composites*, Surf. Coat. Technol., 14, 45.
98. Ivosevic, M., Knight, R., Kalidindi, S.R., Palmese, G.R., Sutter, J.K., (2006). *Solid particle erosion resistance of thermally sprayed functionally graded coatings for polymer matrix composites*, Surf. Coat. Technol., 2006, 5145.
99. Ivosevic, M., Knight, R., Kalidindi, S.R., Palmese, G.R., Sutter, J.K., (2003). International Thermal Spray Conference and Exposition (ITSC2003), ASM International, Orlando, Florida, USA, p. 1667.
100. Yugeswaran, S., Selvarajan, V., Seo, D., Ogawa, K., (2008). *Effect of critical plasma spray parameter on properties of hollow cathode plasma sprayed alumina coatings*, Surf. Coat. Technol., 203, 129–136.
101. Song, E.P., Ahn, J., Lee, S., Kim, N.J., (2006). *Microstructure and wear resistance of nanostructured Al2O3–8 wt.% TiO2 coatings plasma-sprayed with nanopowders*, Surf. Coat. Technol., 201, 1309–1315.
102. Goberman, D., Sohn, Y.H., Shaw, L., Jordan, E., Gell, M., (2002). *Microstructure development of Al2O3–13 wt.% TiO2 plasma sprayed coatings derived from nanocrystalline powders*, Acta Mater., 50, 1141–1152.
103. Tekmen, C., Tsunekawa, Y., Okumiya, M., (2008). *Effect of plasma spray parameters on inflight particle characteristics and in-situ alumina formation*, Surf. Coat. Technol., 203, 223–228.
104. Chen, S.H., Liu, L., Wang, T.C., (2005). *Investigation of the mechanical properties of thin films by nanoindentation, considering the effects of thickness and different coating-substrate combinations*, Surf. Coat. Technol., 191, 25–32.
105. King, R.B., (1987). *Elastic analysis of some punch problems for a layered medium*, Int. J. Solids Struct., 23,1657–1664.
106. Saha, R., Nix, W.D., (2002). *Effects of the substrate on the determination of thin film mechanical properties by nanoindentation*, Acta Mater., 50, 23–38.
107. Wenzhi, H., Xiayun, G., Ling, Z., (2018). *Fabrication and property of novel double-layer coating deposited on polyimide matrix composites by atmospheric plasma spraying*, Ceramics International, 44, 5473–5485.
108. Chen, S., Xiang, J., Huang, J., Zhao, X., (2015). *Microstructures and properties of doubleceramic-layer thermal barrier coatings of La2(Zr0.7Ce0.3)2O7/8YSZ made by atmospheric plasma spraying*, Appl. Surf. Sci., 340, 173–181.

Received: July 7, 2022 / Accepted: December 15, 2022 / Paper available online: December 20, 2022 © International Journal of Modern Manufacturing Technologies