



HAL
open science

Coatings for Space-Based Systems: Impacts of Plasma Processes

Richard Clergereaux, Veronica Orlandi, Myrtil L Kahn, Grégory Navarro,
Alexis Paillet

► **To cite this version:**

Richard Clergereaux, Veronica Orlandi, Myrtil L Kahn, Grégory Navarro, Alexis Paillet. Coatings for Space-Based Systems: Impacts of Plasma Processes. 52nd International Conference on Environmental Systems, Jul 2023, Calgary, Canada. hal-04235779

HAL Id: hal-04235779

<https://hal.science/hal-04235779>

Submitted on 10 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Coatings for Space-Based Systems: Impacts of Plasma Processes

Richard CLERGEREAUX¹ and Veronica ORLANDI²
CNRS-Laplace, Toulouse, France

Myrtil L. KAHN³
CNRS-LCC, Toulouse, France

and

Gregory NAVARRO⁴ and Alexis PAILLET⁵
CNES, Spaceship, Toulouse, France

Plasma assisted processes have become more and more important in surface treatments applied to different domains. For example, thin metallic films, dielectric layers or hard coatings with functional properties related to the material structure and composition are widely used in different fields of applications. Nowadays, multifunctional coatings are also highly required. For example, sustainable activated filters, protective layer to reduce system ageing, as well as combined superhydrophobic, anti-fouling and resistant coatings are expected in various terrestrial applications. Nanocomposite thin films *i.e.* coatings of matrix-embedded nanoparticles are potential candidates as they are exhibiting multifunctional properties related to the matrix and the nanoparticles and, especially, their concentration, size, shape, and distribution in the coating. Different plasma strategies are developed. This presentation aims to review different plasma assisted technologies to form innovative coatings and their potential impacts for space-based systems with a specific focus on safer-by-design methods.

I. Introduction

Over the years, significant research efforts have been devoted to protecting, modifying, or improving material properties. This process involves functional coating deposition. On Earth, many application of functional coatings have already been found and developed. The need to contrast ageing of materials and structures (during their storage and/or operation) ¹⁻²⁻⁷ is a prime example. A huge number of processes and coatings with different thicknesses, compositions and structures have been produced for their anti-scratch, anti-corrosion, anti-fouling, anti-UV or (super-)hydrophobic properties. However, ageing is due to combined effects (environmental, weathering, temperature, mechanical constraint, etc.) and its prevention cannot be obtained with one single material. The use of coatings with the adequate properties is then relevant to protect materials and to prevent or, at least, decelerate their ageing ⁸.

(Nano-)composite coatings, *i.e.* films with embedded (nano-)particles, are foreseen as new protective materials able to combine those physical and chemical properties. For example, General Electric patented ceramic matrix composites to replace certain metallic components in engines' hot sections ⁹ preventing ageing and corrosion during heat cycling. Another example of application is related to human spaceflight, where filters with embedded nanoparticles are attractive to catalyze gases destruction (methane and carbon dioxide, ammonia or acetone, methyl alcohol and carbon monoxide that are byproducts of metabolism) ^{10,11} as well as to kill or filter pathogens ¹² for air treatment. Nowadays, the new generations of nanocomposites are at a higher level of sophistication and are developing

¹ Directeur de Recherche au CNRS, SCIPRA, 118 Rte de Narbonne 31077 Toulouse France.

² PhD student cosupervised by 1, 3 and 5, SCIPRA, 118 Rte de Narbonne 31077 Toulouse France.

³ Directeur de Recherche au CNRS, NOS, 205 Rte de Narbonne 31400 Toulouse France.

⁴ Spaceship France project Engineer responsible for the development of habitat and life support system, CNES, 18 avenue Edouard Belin 31401 Toulouse France.

⁵ Spaceship France project Manager, CNES, 18 avenue Edouard Belin 31401 Toulouse France.

multifunctionalities. For example, anti-reflective coatings with anti-UV properties for windows ¹³ combined electromagnetic shielding and thermal deicing functionalities ¹⁴.

For their versatility, multifunctional nanocomposites are not only interesting for Earth applications. These materials already find some remarkable applications in different fields of the space industry, and they will continue to be interesting provided the future developments of the sector. In particular, coatings can become a key factor for the development of technologies related to the human space exploration.

Different deposition methods involving wet or dry processes were developed, producing nanocomposites with valuable properties. However, an ideal task deals with the production of such coatings with high efficiency (with most of the chemical inputs converted), small impacts for humans and their environment (from the point of view of inputs but also of by-products), as well as reduced cost, not only in the economical point of view but also in terms of environment, health and energy.

Plasma processes, especially the nonthermal ones, tackle some of these recommendations. They consist of gaseous discharges produced in closed reactors with dynamical researches ¹⁵⁻¹⁸ as well as industrial developments ^{19,20}. The objective of this paper is to provide a review of various plasma processes and their potential to produce advanced coatings, focusing in particular on the latest and safer production methods. Moreover, the paper sheds light on the current and prospective applications of thin coatings in the realm of spaceflight, including human spaceflight, along with their associated benefits.

II. Introduction to plasma physics

A plasma is a system of energy conversion into light, kinetic energy and/or chemical reaction. It consists of an electrical conducting gas formed of electrons, ions, photons, excited species, radicals and molecular fragments with neutrals. In contrast with fully ionized plasmas *e.g.* stars, low-temperature plasmas are systems where reactive species are formed by free electron - neutral collisions. These conditions define the term plasma as it is referred to throughout the rest of this review.

Plasmas are found in a growing list of successful practical applications such as ozone generation, excitation of laser and excimer lamps, and are currently under development for use in electronic devices ²¹ (for sputtering, etching, stripping, cleaning in microelectronics), analytical analyses (with the applications of ICP-MS/OES or LIBS ²²), health and environment (with plasma sterilization ²³ and biological decontamination, medical treatments), electric propulsion (plasma thrusters ²⁴, aerodynamic flow control), and for coatings.

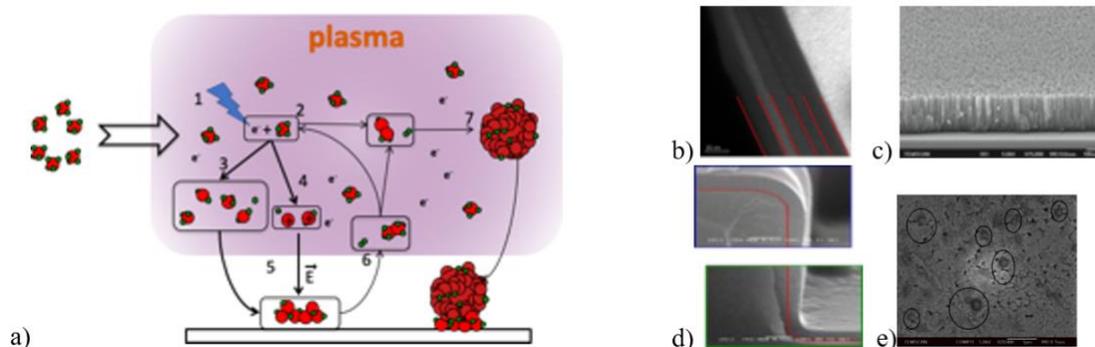


Figure 1. Schematic of a plasma process. *a)* a deposition process involves (1) electron heating, (2) electron-neutral collisions inducing (3) molecular dissociation and 4) ionization. The 5) transport and recombination of reactive species lead to the formation of a thin film. It is possible to obtain smooth single or *b)* multiple layers, *c)* nanotextured on 2D or *d)* 3D substrates. Of note, while radicals are diffusing to the walls, ions are transported by electric fields – the latter controlling ions kinetic energy. Additional mechanisms of 5) desorption and 6) recombination in the plasma volume can also be involved, leading to aggregation 7). The latter induce the formation of *e)* nanocomposite thin films.

Plasmas processes are produced and developed in a wide range of pressures (from atmospheric pressure to 0.1 Pa) with different sources (DC, AC, pulsed) and different reactor configurations (capacitively or inductively coupled).

Figure 1 summarizes some of the mechanisms generally involved. Electrons are the driving species of the discharge. In laboratory, the kinetic energy of free electrons rises by coupling their dynamics with electromagnetic fields (1 in Figure 1). When they reach the critical energy of gas dissociation or ionization, they can form upon

collisions (2) various species as radicals, fragments, atoms (3) or ions (4)^{25,26,27}. These reactive species can initiate a thin film deposition (5) in the so-called Plasma Enhanced Chemical Vapor Deposition (PE-CVD), that will be discussed in Section III. Furthermore, the desorption of reactive species from the substrate can cause recombination in the plasma volume (6). This can lead to the formation of aggregates and/or nanoparticles, that can participate in the growing of the thin film (7). In-situ formation of nanoparticles will be discussed in Section IV.

III. PE-CVD for functional thin film deposition

As shown in Figure 1, surface recombination and thin film growth can occur depending on the chemical structure of the reactive species and their transport to the substrate surface (5). The thin film growth mechanisms, structure and, consequently, properties are directly dependent on the reactive gas composition, as well as the process conditions (for example the pressure, the excitation frequency, or the reactor geometry). In addition, PE-CVD enables to form homogeneous single or multilayer structures (Figure 1.b), smooth or micro-nanotextured (Figure 1.c) on flat or 3D substrates (Figure 1.d). Hence, PE-CVD has garnered great attention for preparing thin films with a wide scope of functionalities at low temperatures and in a controlled manner. These functionalities are applied to:

- lighting and imaging (light emitting diodes²⁸, colored glasses and filters, smart windows, field emitting devices²⁹),
- communication (optical switches and fibers, controlled or graded optical indexes coatings) and data storage (optical, magnetic memories^{30,31}),
- energy production and storage (solar cells³², batteries, hydrogen storage³³, fuel cells & tanks),
- sensors (magneto restrictive materials, high-temperature superconductors, gas, chemical, UV and optical sensors³⁴, smoke or ice detectors),
- protective coatings (water repellent, superhydrophobic, corrosion protective, non-flammable³⁵, auto-cleaning, gas or solvent barriers, acid resistant coatings, high friction coefficient materials³⁶, scratch resistant, malleable, anti-fouling³⁷),
- pharmacology (medical implants, biocompatible³⁸ or biocide coatings³⁹, controlled drug release or delivery systems),
- catalysis (photo and stereo selective),
- etc.

For these applications, various reactive precursors are used. A first example deals with silane (Figure 2.a) that enables forming structures going from amorphous silicon³² to silica⁴⁰ in the presence of oxidizing agents. Another example deals with methane (Figure 2.b) that can form hydrocarbon layers with concentrations of carbon hybridized sp^2 (graphite) or sp^3 (diamond) and hydrogen directly controlled by the process. While highly resistant “diamond-like carbon” (DLC) are generally obtained due the ion bombardment of low-pressure asymmetrical RF plasmas^{41,42,43}, soft polymers are obtained at atmospheric pressure. Notably, these coatings are useful to protect functional surfaces against wear, friction, and other tribological phenomena^{41,42} and for tissue engineering⁴⁴, respectively. PE-CVD is not the only method for thin film deposition; other methods exist, notably the Physical Vapor Deposition processes (PVD), the most famous of which exploits the phenomenon of sputtering by ion bombardment⁴⁵.

One of the challenges related to thin film deposition is the manipulation of precursors, as some gases are toxic and others are extremely flammable and pyrophoric (e.g., silane and methane). As a result, vapors of liquid compounds are used nowadays^{46,47}. Different methods have also been developed to inject such precursors into plasmas. Before the 1970s, the delivery of liquid precursors was generally done using “bubblers”. These consisted of bottles containing the precursor, ideally a liquid with a significant vapor pressure. The precursor was then delivered, drove by a carrier gas that was fed through the liquid and that became fully saturated with the precursor on passing through the bubbler.

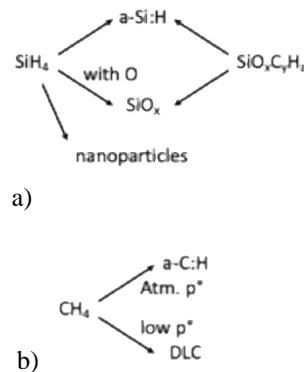


Figure 2. Example of coatings obtained by PE-CVD. The film structure and properties are directly controlled by a) the gas composition, for example, silane with oxidative agents or b) the plasma conditions.

Nowadays, the more conventional approach deals with the thermal heating of liquid containers regulated by a mass flow controller. The vapor can also originate from a liquid source using special liquid mass flow controllers for the direct regulation of liquid delivery. The liquid is then fed to a vaporizer to produce a vapor of the precursor at the point of use.

IV. Plasma nanotechnologies

Figures 1.a, 1.e, and 2.a suggest that nanoparticles, *i.e.* particles with at least one dimension less than 1 μm , can also be formed in the plasma, along with thin films. This discovery leads us to explore a new field of investigation related to nanotechnologies. In contrast with bulk material, such nanoparticles are showing original properties related to their characteristic, size and shape. With the nanoparticle size, surface properties are improved. For example, 1 m^3 of a bulk material has a surface of 6 m^2 . In the nano-world, it corresponds to $2.4 \cdot 10^{23}$ nanoparticles of 10 nm radius and, consequently, to a developed surface of $3 \cdot 10^8 \text{ m}^2$. It also introduces quantum effects affecting the optical, electrical, and magnetic behavior of materials.

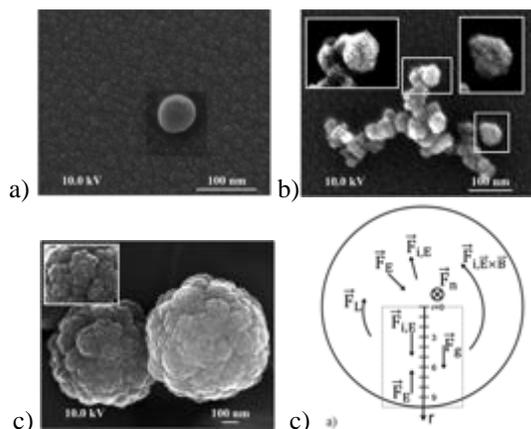


Figure 3. SEM images of nanoparticles formed in a low pressure magnetized plasma ⁴⁷. Depending on the experimental conditions, a) isolated nanoparticles, b) aggregates or c) microparticles can be formed. These structures are controlled by d) the balance of forces.

Nanoparticles can be formed, for example, during PE-CVD processes. As seen in Figure 1, during film growth, recombination on the surface can produce by-products from surface desorption (5). Additional mechanisms can also intervene, such as recombination in the plasma volume (6) (as shown in Figure 2a). The latter can further lead to the generation of nano- to micron-sized particles (as shown in Figure 3a, b, and c) in the so-called "dusty plasmas" ^{48,49}, leading eventually to what is referred to as *in-situ* formation of nanoparticles.

Nanoparticles can efficiently grow while remaining confined within a specific volume until they reach a critical size. This critical size is determined by the balance of forces acting on the particles, with the electrostatic force being one of the most significant. When nanoparticles are immersed in the plasma, they collect electrons and ions, resulting in a negative charge. This charge is directly influenced by both the plasma and nanoparticle characteristics. Various forces such as neutral and ion drag, thermophoretic forces, and gravity contribute to the transportation of dust particles, ultimately leading to their deposition on the reactor walls. As a result, the size of nanoparticles is directly controlled by the characteristics of the plasma.

It is important to notice that nanoparticles are difficult to manage whenever they are not embedded in a matrix, as they can, for instance, be harmful for the users and environment ⁵⁰. This is why nanocomposite thin films, *i.e.* thin films with embedded nanoparticles, are highly developed.

V. Nanocomposite thin film deposition

Plasma deposition of nanocomposite thin films is foreseen to form new protective coatings combining different physical and chemical properties. Unlike homogeneous coatings, nanocomposites allow for the production of multifunctional thin films that have applications in a wide range of fields. The composition, concentration, size, shape, and distribution of nanoparticles, which are isolated and finely dispersed in the matrix, contribute to the overall properties of the thin films, in addition to the characteristics of the matrix itself. An example of an application is related to the aging of structures or materials, which is caused by a combination of environmental factors such as weathering, temperature, mechanical constraints, and other stressors. Preventing or slowing down this aging process cannot be achieved through the use of a single material alone. Instead, the application of protective and multifunctional coatings with appropriate physical and mechanical properties is a crucial method for protecting materials from environmental stresses and slowing down their aging process. Moreover, the properties of nanocomposite materials are not only given by the sum of the individual contributions of the matrix and the nanoparticles, but are also related to the interfaces between them. The role of the inner interfaces is especially important for smaller nanoparticles.

Overall, the deposition of nanocomposite thin films is achieved through various plasma-assisted methods. These methods can involve either chemical or physical processes and may also involve post-treatment techniques. Some notable examples are listed below:

The simplest plasma process, based on the deposition of chemicals, involves the use of complex organometallic compounds as the reactive precursors in PE-CVD. After plasma injection, this kind of precursors can form metal-organic nanocomposite coatings with metallic nanoparticles embedded in an organic matrix⁵¹. Although this method has demonstrated effectiveness, it has limited applicability due to specific requirements. Specifically, the precursor must be both volatile enough for thin film processing and stable during storage, manipulation, and use. Furthermore, the method's versatility is restricted, as the resulting nanocomposite film structure is directly tied to the precursor's structure.

As previously mentioned, various physical methods for nanocomposite production have also been developed. Physical methods can be combined with chemical deposition methods such as PE-CVD to co-deposit nanoparticles and the matrix (as shown in Figure 2). Metal evaporation, PVD, or laser ablation, coupled with PE-CVD⁵² are commonly used methods. For example, in PVD/PE-CVD, nanoparticles are produced from a target simultaneously with the deposition of the matrix, allowing for the deposition of various nanocomposite thin films in low-pressure plasmas. However, these strategies are more expensive and challenging than other methods. These processes are generally operated at low-pressure, and the type, size and structure of the nanoparticles are directly imposed by the deposition conditions (pressure, reactor dimensions, use of shower electrodes, etc.).

Finally, it is possible to develop nanocomposite thin films by depositing sub-stoichiometric materials, but this process requires post-treatments such as heating. For example, heating SiN_x thin films obtained by PE-CVD in SiH₄ / NH₃ mixtures during 1 h at 1100°C leads to the formation of few nm silicon nano-crystals embedded in the matrix⁵³. However, a major drawback of this process is that the post-treatment can be destructive for substrates made of alloys or polymers. Additionally, the use of sub-stoichiometric materials does not allow for the formation of a wide range of materials. Ultimately, achieving fine control over the nanocomposite structure through post-treatment techniques remains a significant challenge.

All of the aforementioned approaches have a common thread, as they involve the in-situ formation of nanoparticles. In this context, aerosol injection in plasmas is a versatile method that allows for the simultaneous injection of both nanoparticles and the matrix precursor. This process involves injecting micrometer-sized droplets into a gas phase directly into the downstream process, in larger quantities than vapors and regardless of their composition or properties. For example, the drops can a mixture of liquids, a dispersion of nanoparticles, or a colloidal solution. Notably, the droplets sprayed in the aerosol can contain nanoparticles that are already included in the precursor solution before entering the plasma. This method has been extensively applied in the field of chemical vapor deposition (CVD) and atomic layer deposition (ALD)⁵⁴ and has attracted increasing interest in plasma-enhanced chemical vapor deposition (PE-CVD)⁵⁵. For example, nanocomposites were produced using a solution of metal (gold) salts dissolved in a polymerizable solvent (isopropanol) or colloidal solutions with metal-oxide (ZnO, TiO₂) nanoparticles injected in low- and atmospheric-pressure plasmas. This method provides a higher versatility than any other method to produce multicomponent coatings⁵⁶. However, it is not possible to use the classical delivering systems as defined in Part III. Moreover, the treatment of nanoparticles *ex-situ* can be dangerous for the user and the environment, while their insecure handling before any further process implementation can compromise their direct application.

VI. Aerosol-assisted plasmas

Different systems exist for injecting a precursor into plasma. Delivery systems can be classified into the following categories: the precursor can be injected (1) as a vapor of the precursor(s) solution, (2) from solid delivery systems, where the precursor is vaporized directly from solid, or (3) from aerosol-assisted delivery systems, where an aerosol containing the precursor is formed prior to delivery. An example of this last category is the Direct Liquid Injection (DLI), which is used to deliver liquid precursors or a solution containing all the required precursors and/or nanoparticles in the plasma. The solution is transported, often via a syringe, to a vaporization chamber where it is vaporized. However, this method provides a continuous flow of droplets in the plasma phase, which results in the creation of the so-called misty plasma^{57,58}. Similar to dusty plasmas, misty plasmas can result in additional losses due to collisions, which can impact the ionization rate and consequently the deposition rate. Additionally, the evaporation of liquid droplets in the plasma phase increases the pressure⁵⁹, leading to further modifications in the plasma and in the deposition process behavior.

Alternative means of continuous aerosol injection into the plasma include the Pulsed, Direct Liquid Injection (PDLI) ⁶⁰ system. Although the pulsed injection temporarily affects the plasma, a stationary state is restored between pulses, and the process can return to an equilibrium state ⁵⁹. It is interesting to study how PDLI can influence the deposition process behavior (deposition rate, nanoparticles dispersion, ...).

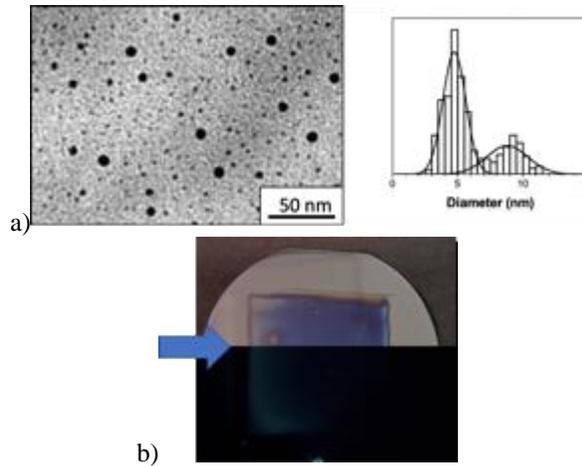


Figure 4. Coatings obtained with the pulsed injection of a colloidal solution. *a) reports a TEM image of the nanocomposite thin film deposited at low-pressure with the nanoparticle size distribution and b) pictures of the coating obtained at atmospheric pressure (the bottom image was taken under UV irradiation).*

The difficulty in obtaining coatings with specific characteristics (with respect to nanoparticles dispersion, size, homogeneity, etc.) shows that aerosol-assisted processes cannot be considered a “plug and play” solution, and their implementation must involve the effort of chemists, physicists and engineers.

Recently, a secure, versatile, and synthetic methodology, compatible with pulsed injections, has been developed for the formation of nanoparticles. This approach, called pulsed direct liquid reaction-injection (DLRI), allows for a safe-by-design in situ synthesis of nanoparticles prior to their direct injection as an aerosol ⁶⁰. DLRI is compatible with various processes, including plasma processing ⁶¹. The TEM image of the nanocomposite thin film deposited at low-pressure (Figure 5.a), shows a ZnO/DLC nanocomposite with inclusions of well-dispersed, non-aggregated nanoparticles with an average diameter of 6 nm. As before, results obtained at various pressures are presented to showcase the versatility of plasma processing. Consequently, Figure 5.b demonstrates the deposition at atmospheric pressure. It is evident that the coating forms in the region between the electrodes. However, upon observing the image taken under UV irradiation, a higher fluorescence is noticeable at the discharge entrance. It means that nanoparticles are rapidly deposited on the substrate while the matrix deposition takes place all along the discharge cell.

These two examples show that pulsed injection enables to form original nanocomposite thin films. However, the pulsed mode induces a lot of mechanisms (flow, transport, discharge) that must be investigated. Indeed, since the process parameters vary significantly in pulsed injection mode, it is important to assess the characteristics of the

For this purpose, Figure 4 shows images of nanocomposite thin films obtained through PDLI of colloidal solutions containing fluorescent ZnO nanoparticles of 6 nm in diameter dispersed in pentane. To demonstrate the versatility of plasma processing, both low-pressure and atmospheric-pressure deposits are shown in the figure.

The deposited material consists of a DLC matrix with highly dispersed nanoparticles that exhibit optical and mechanical properties. However, the size distribution highlights the presence of two populations of nanoparticles, with sizes around 6 and 10 nm. While the first population corresponds to the initial nanoparticles, the second population suggests that the nanoparticles aggregate during the process, especially in the droplets.

Figure 4.b shows pictures of a similar nanocomposite thin film deposited at atmospheric pressure. The coating, limited to the region between the electrodes, is homogeneous. However, the image taken under UV irradiation (bottom of Fig. 4b) shows a slight fluorescence characteristic of a small quantity of nanoparticles embedded in the matrix.

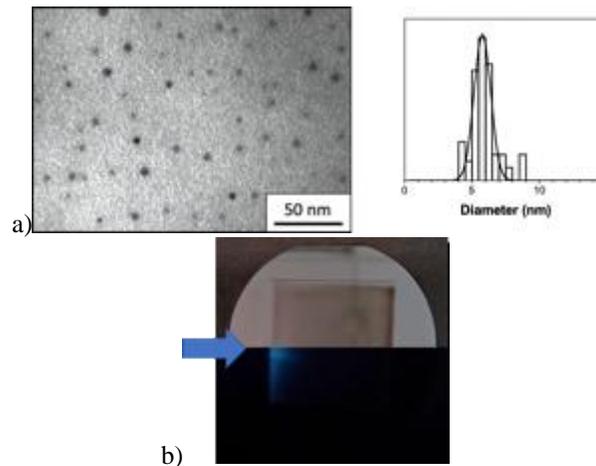


Figure 5. Coatings obtained with the pulsed direct liquid reactor-injector of nanoparticles (DLRI). *a) at low-pressure and b) at atmospheric pressure.*

aerosols and their effects on the global process of the plasma, the plasma-surface interactions and the resulting deposited material.

VII. Thin films' applications for the future of space exploration

As briefly mentioned in Section I, plasma deposition techniques have already made significant contributions to the space industry. As space exploration, particularly human spaceflight, expands in the coming years, there will be even greater motivation to discover and develop new applications of nanocomposite materials, which will be able to offer both efficiency and economic advantages. While various applications already exist in the space domain, here the focus is particularly on the future potential applications of thin films and nanocomposites that already find their purpose on Earth and that can be useful for the future of space exploration.

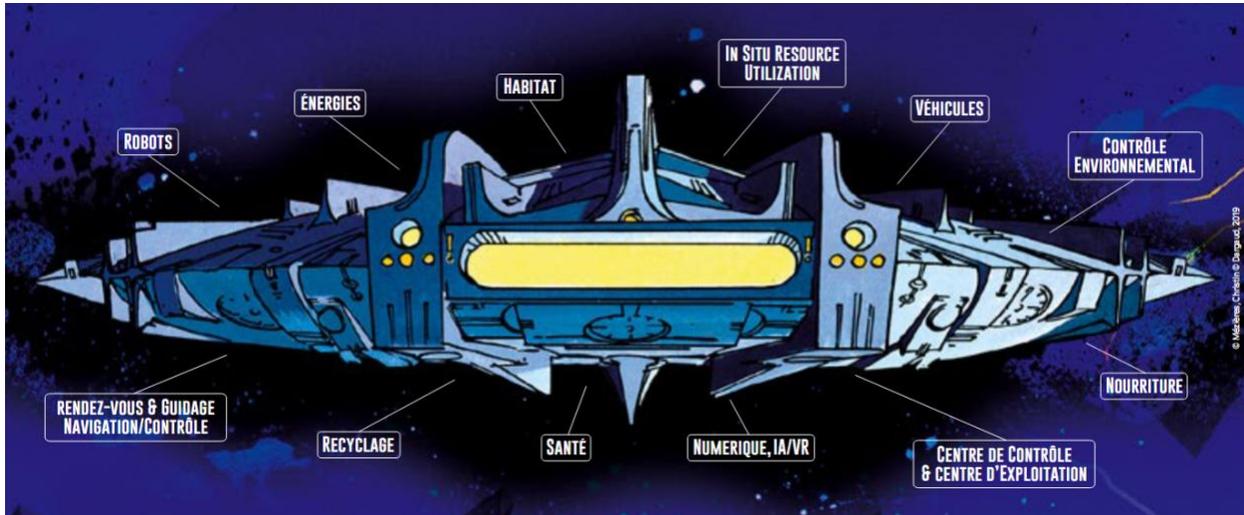


Figure 6. The 12 axes of research for human space exploration. *Translated in English a) Robots b) Energy c) Habitat d) In Situ Resources Utilization d) Vessels e) Environmental control f) Food g) Control center & Exploitation center h) Numerical, Artificial Intelligence (AI) and Virtual Reality (VR) i) Health j) Recycling k) Rendez-vous and guidance navigation/control.*

In order to look at the role of plasma processing in the future of space missions, a list of 12 challenges related to human space exploration as reported by Spaceship FR is schematized in Figure 6. Out of these 12 challenges, at least 8 can be addressed by plasma processes with the implication of thin films or nanocomposites. In particular:

- **Robots:** Future Lunar and Martian rovers could be coated with thin films that offer various properties, such as anti-scratch, anti-reflection, or anti-dust adhesion ^{62,63,64}. By incorporating nanoparticles, it is possible to create multifunctional materials that combine these properties and even exhibit self-healing characteristics ^{65,66}. The use of plasma processed materials can limit structural damages, thereby reducing the need for maintenance and redundancy, and extending the lifespan and efficiency of the rovers.
- **Energy:** Thin films and nanocomposites are already studied and used to develop and enhance the performance and durability of fuel cells, photovoltaic cells or battery elements that are widely used in space ⁶⁷⁻⁷⁰. Improving their efficiency means widening the use of this rather reliable and flexible energy sources.
- **Habitat:** Just like rovers, Lunar habitats will need to be protected from the surrounding environment. In particular, structural damages and wear need to be avoided due implications related to safety and costs. Therefore, the use of thin films and multifunctional composites with anti-scratch, anti-radiation, and self-healing properties can be explored as a means of safeguarding these habitats ^{71,72,73}.
- **Vessels:** Coatings with properties such as anti-scratch, anti-corrosion, anti-UV, and (super-)hydrophobic effects are already widely utilized in the aviation and space industry ⁷⁴⁻⁷⁷. These characteristics can be exploited and combined to contrast wear and aging of materials in the new vessels for space exploration, participating in crew's safety and maintenance costs.

- **Environmental control:** Plasma processes have already been used to synthesize and prepare different kind of catalysts. In particular, catalytic thin films, usually made of a support embedded in nano-sized particles, have been already used for environmental control purposes. Those material can be in fact used as gas sensors, photocatalysts or even fuel cells electrodes^{78,79}. Plasma technology holds great potential for improving catalyst location control and reducing loading, thus enabling miniaturization for mobile applications or lab-on-chip system. Additionally, it enhances control over the quality of synthesized materials, leading to improved catalytic performance.
- **Food:** Superhydrophobic coatings are currently being studied for their promising applications in the food industry. Their most interesting characteristics that can also be exploited for space use include their anti-bacterial and anti-fouling properties, which prevent the proliferation of harmful microorganisms, and their anti-corrosion properties, which prevent wear in food packaging⁸⁰⁻⁸³. Additionally, these coatings can be used to reduce drag accumulation in the pipelines of food facilities, which can help reduce production costs⁸⁴.
- **Health:** Biocidal or biocompatible materials can be used to monitor the presence of bacteria in the constantly recycled atmospheres of human habitats, as exemplified by the Matiss project, an experiment selected by the Centre National d'Etudes Spatiales (CNES)^{*}. Moreover, thin films and nanocomposites can be applied on textile materials to control different properties, like solar and heat flows. These characteristics can be integrated in the new spacesuits as part of the life support system to allow for longer extra-vehicular activities⁸⁵.
- **Recycling:** Inefficient food packaging often results in large amounts of food sticking to the walls of envelopes. This problem not only creates economic and ethical concerns on Earth but is exacerbated when considering human habitats in space. A solution can be found in the use of superhydrophobic surfaces with low wettability, that can reduce liquid food waste related to packaging⁸⁶. Additionally, these surfaces can be utilized to minimize waste in food production facilities⁸⁷.

Although this list is not exhaustive, it provides a glimpse of the increasingly important role that plasma processing could play in the future of the space industry. Indeed, many more applications can be found for thin films and multifunctional materials, thanks also to versatile techniques of deposition such as the aerosol-assisted plasma deposition that will allow for the manufacturing of new materials.

VIII. Conclusion

Plasma assisted processes have become more and more important in surface treatments applied to different domains and they already find their application in different fields of the aviation and space industry. Nanocomposite thin films, *i.e.* coatings of matrix-embedded nanoparticles, are particularly interesting due to their multifunctional properties that arise from the combination of both the matrix and the nanoparticles. The concentration, size, shape, and distribution of the nanoparticles in the coating play a crucial role in determining these properties.

In this paper, different thin films and nanocomposite deposition strategies were reviewed. Among them, the simplicity and versatility of the aerosol-assisted methods were highlighted. However, these processes meet hard points related to (1) nanoparticles specifications, (2) process implementations and (3) environmental, safety risks and life cycle. Specifically, these methods often involve handling nanoparticles, at least during the preparation of the liquid dispersion, which can have adverse effects on human health and the environment. These limitations can be tackled by coupling chemistry, physics and engineering to create a safe-by-design solution.

Finally, the potential importance of thin films and nanocomposite materials in the future of space exploration was demonstrated by providing a list of mostly Earth-based applications of these materials that can prove fundamental in space systems.

Acknowledgments

This work was financially supported by the Centre National de la Recherche Scientifique (CNRS), the STAE-RTRA foundation (Toulouse, France) under the RTRA-STAE/2014/P/VIMA/12 project grant, the National Science and Engineering Research Council in the context of the Alliance project grant, and Prima-Québec. Financial support from the CNRS, the Université de Montréal and the Université de Toulouse III – Paul Sabatier through their

* European Space Agency, MATISS ESA, 2016, URL: https://www.esa.int/ESA_Multimedia/Images/2016/09/Matiss [cited 8 May 2023]

contributions to the International Research Network on Controlled Multifunctional Nanomaterials (IRN NMC) is also acknowledged.

References

- ¹van Breugel, K., Koleva, D., van Beek, Ton., *The ageing of materials and structures: Towards scientific solutions for the ageing of our assets*, Springer Science+Business Media, 2017.
- ²Schneider, E. and Stilp, A. "Micrometeorite Impact Simulation at EMI — A Review," *International Journal of Impact Engineering*, Vol. 5, No. 1-4, 1987, pp. 561-568.
- ³Prasad, N. and Wanhill, R., *Aerospace Materials and Material Technologies: Volume 1: Aerospace Material*, 2017.
- ⁴Paulmier, T., Dirassen, B., Payan, D., and Eesbeek, M., "Material Charging in Space Environment: Experimental Test Simulation and Induced Conductive Mechanisms," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 16, No. 3, pp. 682-688, 2009.
- ⁵Gigliotti, M. and Grandidier, J.-C., "Preface to the theme issue 'Durability and ageing of composite materials'," *Philosophical Transactions of the Royal Society A*, Vol. 381, 2022.
- ⁶J. Chen, N. Ding, Z. Li, and W. Wang, "Organic polymer materials in the space environment," *Progress in Aerospace Sciences*, Vol. 83, pp. 37-56, 2016.
- ⁷Hibbs, A. R., "The distribution of micrometeorites near the Earth," *Journal of Geophysical Research*, Vol. 66, No. 2, pp. 371, 1961.
- ⁸Bucci, R. J., Warren, C. J., and Starke, E. A., "Need for new materials in aging aircraft structures," *Journal of Aircraft*, Vol. 37, No. 1, pp. 122-129, 2000.
- ⁹Shah, T.K., Malecki, H.C., and Carson, M.N., (n.d.).
- ¹⁰Castro, V., Bruce, R., Ott, C., and Pierson, D., "The Influence of Microbiology on Spacecraft Design and Controls: A Historical Perspective of the Shuttle and International Space Station Programs," *SAE Technical Paper 2006-01-2156*, 2006.
- ¹¹S. Aithal and P. Aithal, *Environmental Information Sciences: With Aspects on Allied Areas & Other Emerging Interdisciplinary Environmental Concerns*, edited by PK Paul et al. Published by New Delhi Publishers, New Delhi, India, pp. 13, 2020.
- ¹²Wilson, M., Cole, H., Rector, T., Steele, J., and Varsik, J., "International Space Station (ISS) Internal Active Thermal Control System (IATCS) New Biocide Selection, Qualification and Implementation," *41st International Conference on Environmental Systems*, pp. 5006, 2012.
- ¹³Pokorny, R.J., Klun, T.P., Radcliff, R.J., Kamrath, R.F., and Wlaker, C.B.Jr., (n.d.).
- ¹⁴D'Amore, M., Greco, S., Lampasi, D. A., Sarto, M. S., and Tamburrano, A., "A New Structure of Transparent Films for Heat Control and Electromagnetic Shielding of Windows," *2009 International Symposium on Electromagnetic Compatibility - EMC Europe*, 2009.
- ¹⁵Adamovich, I., Agarwal, S., Ahedo, E., Alves, L.L., Baalrud, S.D., Babaeva, N.Y., Bogaerts, A., Bourdon, A., Bruggeman, P.J., Canal, C., and al. "The 2022 Plasma Roadmap: Low Temperature Plasma Science and Technology," *Journal of Physics D: Applied Physics*, Vol. 55, No. 37, pp. 373001, 2022.
- ¹⁶Samukawa, S., Hori, M., Rauf, S., Tachibana, K., Bruggeman, P., Kroesen, G., Whitehead, J.C., Murphy, A.B., Gutsol, A.F., Starikovskaia, S., and others, "The 2012 Plasma Roadmap," *Journal of Physics D: Applied Physics*, Vol. 45, No. 25, pp. 253001, 2012.
- ¹⁷Adamovich, I., Baalrud, S., Bogaerts, A., Bruggeman, P., Cappelli, M., Colombo, V., Czarnetzki, U., Ebert, U., Eden, J., Favia, P., and others, "The 2017 Plasma Roadmap: Low temperature plasma science and technology," *Journal of Physics D: Applied Physics*, Vol. 50, No. 32, pp. 323001, 2017.
- ¹⁸Bogaerts, A., Tu, X., Whitehead, J.C., Centi, G., Lefferts, L., Guaitella, O., Jury, F., Kim, H.-H., Murphy, A., Schneider, W., Nozaki, T., Hicks, J., Rousseau, A., Thevenet, F., Khacef, A., and Carreon, M., "The 2020 plasma catalysis roadmap," *Journal of Physics D: Applied Physics*, Vol. 53, No. 44, pp. 443001, 2020.
- ¹⁹Roth, J. R., *Industrial Plasma Engineering: Applications to Nonthermal Plasma Processing*, Routledge, 2017.
- ²⁰Graves, D.B., "Plasma processing," *IEEE Transactions on Plasma Science*, Vol. 22, No. 1, pp. 31-42, Feb. 1994.
- ²¹Rogers, B.R. and Cale, T.S., "Plasma processes in microelectronic device manufacturing," *Vacuum*, Vol. 65, No. 3-4, pp. 267-279, 2002.
- ²²Musazzi, S., and Perini, U., *Laser-Induced Breakdown Spectroscopy: Theory and Applications*, Springer, pp. 257, 2014.
- ²³Moisan, M., Barbeau, J., Moreau, S., Pelletier, J., Tabrizian, M., and Yahia, L.H., "Low-temperature sterilization using gas plasmas: a review of the experiments and an analysis of the inactivation mechanisms," *International Journal of Pharmaceutics*, Vol. 226, No. 1-2, pp. 1-21, Sep. 2001.
- ²⁴Miedzic, J., Barral, S., and Daniilko, D., "Influence of oblique magnetic field on electron cross-field transport in a Hall effect thruster," *Physics of Plasmas*, Vol. 22, No. 4, p. 043511, 2015.
- ²⁵Martinu, L. and Poitras, D., "Plasma deposition of optical films and coatings: A review," *Journal of Vacuum Science & Technology A*, Vol. 18, No. 5, pp. 2619-2645, 2000.
- ²⁶De Bleecker, K., Bogaerts, A., Gijbels, R., and Goedheer, W., "Numerical investigation of particle formation mechanisms in silane discharges," *Physical Review E*, Vol. 69, p. 056409, 2004.

- ²⁷De Bleeker, K., Bogaerts, A., and Goedheer, W., "Detailed modeling of hydrocarbon nanoparticle nucleation in acetylene discharges," *Physical Review E*, Vol. 73, p. 026405, 2006.
- ²⁸Le, H.-L. T., Jardali, F., and Vach, H., "Deposition of hydrogenated silicon clusters for efficient epitaxial growth," *Physical Chemistry Chemical Physics*, Vol. 20, pp. 15626-15634, 2018.
- ²⁹Gröning, O., Clergereaux, R., Nilsson, L.-O., Ruffieux, P., Gröning, P., and Schlapbach, L., "Prospects and Limitations of Carbon Nanotube Field Emission Electron Sources," *Chimia*, 2002, Vol. 56, pp. 553.
- ³⁰Jung, K.B., Cho, H., Hahn, Y.B., Lambers, E.S., Onishi, S., Johnson, D., Hurst Jr, A.T., Childress, J.R., Park, Y.D., and Pearson, S.J., "Relative merits of Cl₂ and CO/NH₃ plasma chemistries for dry etching of magnetic random access memory device elements," *Journal of Applied Physics*, Vol. 85, pp. 4788-4790, 1999.
- ³¹Girard, G., Béchu, S., Caillaud, N., Carbone, L., Ortega, L., and Fruchart, D., "Bulk and thin films of magnetic shape memory Ni-Mn-Ga alloys deposited by multi-dipolar plasma-assisted sputtering," *Journal of Alloys and Compounds*, Vol. 465, Issues 1-2, pp. 35-40, 2008.
- ³²Perrin, J., Schmitt, J., Hollenstein, C., Howling, A., and Sansonnens, L., "The physics of plasma-enhanced chemical vapour deposition for large-area coating: industrial application to flat panel displays and solar cells," *Plasma Physics and Controlled Fusion*, Vol. 42, No. 12B, 2000.
- ³³Shao, H., Wang, Y., Xu, H., and Li, X., "Hydrogen storage properties of magnesium ultrafine particles prepared by hydrogen plasma-metal reaction," *Materials Science and Engineering: B*, Vol. 110, No. 2, pp. 221-226, 2004.
- ³⁴Bubb, D.M., McGill, R.A., Horwitz, J.S., Fitz-Gerald, J.M., Houser, E.J., Stroud, R.M., Wu, P.W., Ringeisen, B.R., Piqué, A., and Chrisey, D.B., "Laser-based processing of polymer nanocomposites for chemical sensing applications," *Journal of Applied Physics*, Vol. 89, pp. 5739-5746, 2001.
- ³⁵Apaydin, K., Laachachi, A., Fouquet, T., Jimenez, M., Bourbigot, S., and Ruch, D., "Mechanistic investigation of a flame retardant coating made by layer-by-layer assembly," *RSC Advances*, Vol. 4, No. 82, 2014.
- ³⁶Meletis, E.I., Erdemir, A., and Fenske, G.R., "Tribological characteristics of DLC films and duplex plasma nitriding/DLC coating treatments," *Surface and Coatings Technology*, Vol. 73, No. 1-2, pp. 39-45, 1995.
- ³⁷Barletta, M., Aversa, C., Pizzi, E., Puopolo, M., and Vesco, S., "Design, development and first validation of 'biocide-free' anti-fouling coatings," *Progress in Organic Coatings*, Vol. 123, pp. 35, 2018.
- ³⁸Bendavid, A., Martin, P.J., Comte, C., Preston, E.W., Haq, A.J., Magdon Ismail, F.S., and Singh, R.K., "The mechanical and biocompatibility properties of DLC-Si films prepared by pulsed DC plasma activated chemical vapor deposition," *Diamond and Related Materials*, Vol. 16, pp. 1616-1622, 2007.
- ³⁹Soumbo, M., Scarangella, A., Villeneuve-Faure, C., Bonafos, C., Roques, C., and others, "Combined effect of proteins and AgNPs on the adhesion of yeast *Candida albicans* on solid silica surfaces," *Proceedings of the 2020 IEEE 20th International Conference on Nanotechnology (IEEE-NANO)*, pp. 242-245, 2020.
- ⁴⁰Chayani, M., Caquineau, H., Despax, B., Bandet, J., Berjoan, R., "Variations in the Physico-Chemical Properties of Near-Stoichiometric Silica Deposited from SiH₄-N₂O and SiH₄-N₂O-He Radiofrequency Discharges," *Thin Solid Films*, Vol. 471, No. 1-2, pp. 53-62, 2005.
- ⁴¹Ward, L., Junge, F., Lampka, A., Dobbertin, M., Mewes, C., and Wienecke, M., "The Effect of Bias Voltage and Gas Pressure on the Structure, Adhesion and Wear Behavior of Diamond Like Carbon (DLC) Coatings With Si Interlayers," *Coatings*, Vol. 4, No. 2, pp. 214-229, 2014.
- ⁴²Clay, K.J., Speakman, S.P., Morrison, N.A., Tomozeiu, N., Milne, W.I., Kapoor, A., "Material Properties and Tribological Performance of RF-PECVD Deposited DLC Coatings," *Diamond and Related Materials*, Vol. 7, pp. 1100-1107, 1998.
- ⁴³Corbella, C., Vives, M., Oncins, G., Canal, C., Andújar, J.L., Bertran, E., "Characterization of DLC Films Obtained at Room Temperature by Pulsed-dc PECVD," *Diamond and Related Materials*, Vol. 13, issues 4-8, pp. 1494-1499, 2004.
- ⁴⁴Girard-Lauriault, P.-L., Mwale, F., Iordanova, M., Demers, C., Desjardins, P., and Wertheimer, M. R., "Atmospheric Pressure Deposition of Micropatterned Nitrogen-Rich Plasma-Polymer Films for Tissue Engineering," *Plasma Processes and Polymers*, Vol. 2, No. 3, pp. 263-270, 2005.
- ⁴⁵Schütze, A., and Quinto, D. T., "Pulsed plasma-assisted PVD sputter-deposited alumina thin films," *Surface and Coatings Technology*, Vol. 162, No. 2-3, pp. 174-182, 2003.
- ⁴⁶Benissad, N., Boisse-Laporte, C., Vallée, C., Granier, A., and Goulet, A., "Silicon dioxide deposition in a microwave plasma reactor," *Surface and Coatings Technology*, Vol. 116-119, pp. 868-873, 1999.
- ⁴⁷Supiot, P., Vivien, C., Granier, A., Bousquet, A., Mackova, A., Escaich, D., Clergereaux, R., Raynaud, P., Stryhal, Z., & Pavlik, J., "Cover Picture: Plasma Process. Polym. 2/2006," *Plasma Processes and Polymers*, Vol. 3, pp. 100-109, 2006.
- ⁴⁸Al Makedssi, G., Glad, X., Dap, S., Rojo, M., Clergereaux, R., and Margot, J., "Influence of a magnetic field on the formation of carbon dust particles in very low-pressure high-density plasmas," *Journal of Physics D: Applied Physics*, Vol. 50, No. 15, 2017.
- ⁴⁹Berndt, J., Kovačević, E., Stefanović, I., Stepanović, O., Hong, S. H., Boufendi, L., and Winter, J., "Some Aspects of Reactive Complex Plasmas," *Contributions to Plasma Physics*, Vol. 49, No. 3, pp. 107-133, 2009.
- ⁵⁰SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), *Opinion on: The appropriateness of existing methodologies to assess the potential risks associated with engineered and adventitious products of nanotechnologies*, 28-29 September 2005.

- ⁵¹Fermi, Y., Kihel, M., Sahli, S., Raynaud, P., "Synthesis of nanopowders in a PECVD reactor from organosilicon precursor," *Phosphorus, Sulfur, and Silicon and the Related Elements*, Vol. 194, No. 10, pp. 978-982, 2019.
- ⁵²Millière, L., Makasheva, K., Laurent, C., Despax, B., Boudou, L., and Teyssedre, G., "Silver nanoparticles as a key feature of a plasma polymer composite layer in mitigation of charge injection into polyethylene under dc stress," *Journal of Physics D: Applied Physics*, Vol. 49, No. 1, p. 015304, 2015.
- ⁵³Barbé, J., Xie, L., Leifer, K., Faucherand, P., Morin, C., Rapisarda, D., De Vito, E., Makasheva, K., Despax, B., and Perraud, S., "Silicon nanocrystals on amorphous silicon carbide alloy thin films: Control of film properties and nanocrystals growth," *Thin Solid Films*, Vol. 522, 2012, pp. 136-144.
- ⁵⁴Vahlas, C., Guillon, H., Senocq, F., Caussat, B., and Bonnafous, S., "Solvent free method for intense vaporization of solid molecular and inorganic compounds," *Gases and Instrumentation*, 2009, pp. 8-11.
- ⁵⁵Mitronika, M., Granier, A., Goullet, A., and Richard-Plouet, M., "Hybrid approaches coupling sol-gel and plasma for the deposition of oxide-based nanocomposite thin films: a review," *SN Applied Sciences*, Vol. 3, no. 6, 2021, p. 665.
- ⁵⁶Fanelli, F., Mastrangelo, A. M., and Fracassi, F., "Aerosol-Assisted Atmospheric Cold Plasma Deposition and Characterization of Superhydrophobic Organic-Inorganic Nanocomposite Thin Films," *Langmuir*, Vol. 30, No. 3, pp. 857-865, 2014.
- ⁵⁷Ogawa, D., Saraf, I., Sra, A., Timmons, R., Goeckner, M., and Overzet, L. J., "The direct injection of liquid droplets into low pressure plasmas," *Journal of Vacuum Science & Technology A - J VAC SCI TECHNOL A*, Vol. 27, pp. 342-351, 2009.
- ⁵⁸Cacot, L., Carnide, G., Kahn, M. L., Clergereaux, R., Naudé, N., and Stafford, L., "Kinetics driving thin-film deposition in dielectric barrier discharges using a direct liquid injector operated in a pulsed regime," *Journal of Physics D: Applied Physics*, Vol. 55, No. 47, 475202, 2022.
- ⁵⁹Sadek, T., Vinchon, P., Durocher-Jean, A., Carnide, G., Kahn, M. L., Clergereaux, R., and Stafford, L., "Time-Resolved Analysis of the Electron Temperature in RF Magnetron Discharges with a Pulsed Gas Injection," *Atoms*, Vol. 10, No. 4, pp. 147, 2022.
- ⁶⁰Carnide, G., Champouret, Y., Valappil, D., Vahlas, C., Mingotaud, A.-F., Clergereaux, R., and Kahn, M. L., "Secured Nanosynthesis-Deposition Aerosol Process for Composite Thin Films Incorporating Highly Dispersed Nanoparticles," *Adv. Sci.*, Vol. 10, pp. 2204929, 2023.
- ⁶¹Carnide, G., Cacot, L., Champouret, Y., Pozsgay, V., Verdier, T., Girardeau, A., Cavarroc, M., Sarkissian, A., Mingotaud, A.-F., Vahlas, C., Kahn, M.L., Naudé, N., Stafford, L., and Clergereaux, R., "Direct Liquid Reactor-Injector of Nanoparticles: A Safer-by-Design Aerosol Injection for Nanocomposite Thin-Film Deposition Adapted to Various Plasma-Assisted Processes," *Coatings*, Vol. 13, No. 3, pp. 630, 2023.
- ⁶²Mauchauffé, R., Kim, J., Kim, D., Lee, S., Kwon, M., and Moon, S. Y., "UV-Shielding TiO₂ Thin Film Deposition on Flexible and Heat-Labile Substrate Using an Open-Air Hybrid CVD/Plasma Method," *Vacuum*, Vol. 192, pp. 110424, 2021.
- ⁶³Li, X., Yu, X., and Han, Y., "Polymer thin films for antireflection coatings," *Journal of Materials Chemistry C*, Vol. 1, No. 12, pp. 2266, 2013.
- ⁶⁴Sabri, F., Werhner, T., Hoskins, J., Schuerger, A. C., Hobbs, A. M., Barreto, J. A., Britt, D., and Duran, R. A., "Thin Film Surface Treatments for Lowering Dust Adhesion on Mars Rover Calibration Targets," *Advances in Space Research*, Vol. 41, No. 1, pp. 118-128, 2008.
- ⁶⁵Metzman, J. S., Wang, G., Morris, J. R., Heflin, J. R., "Enhanced Scratch Resistance of Self-Assembled Silica Nanoparticle Anti-Reflection Coatings," *Journal of Materials Chemistry C*, Vol. 6, No. 4, pp. 823-835, 2018.
- ⁶⁶Li, Y., Chen, S., Li, X., Wu, M., Sun, J. "Highly Transparent, Nanofiller-Reinforced Scratch-Resistant Polymeric Composite Films Capable of Healing Scratches," *ACS Nano*, Vol. 9, No. 10, pp. 10055-10065, 2015.
- ⁶⁷Machado, M., Baiutti, F., Bernadet, L., Morata, A., Nuñez, M., Ouweltjes, J. P., Fonseca, F. C., Torrell, M., Tarancón, A. "Functional Thin Films as Cathode/Electrolyte Interlayers: A Strategy to Enhance the Performance and Durability of Solid Oxide Fuel Cells," *Journal of Materials Chemistry A*, Vol. 10, No. 33, pp. 17317-17325, 2022.
- ⁶⁸Hegde, R. M., Kurkuri, M. D., Kigga, M., "Current Scenario of Nanocomposite Materials for Fuel Cell Applications," *Sustainable Polymer Composites and Nanocomposites*, Inamuddin, S. Thomas, R. Kumar Mishra, and A. M. Asiri, Eds. Cham: Springer International Publishing, pp. 557-592, 2019.
- ⁶⁹Beckel, D., Bieberle-Hütter, A., Harvey, A., Infortuna, A., Muecke, U. P., Prestat, M., Rupp, J. L. M., Gauckler, L. J., "Thin Films for Micro Solid Oxide Fuel Cells," *Journal of Power Sources*, Vol. 173, No. 1, pp. 325-345, 2007.
- ⁷⁰Socol, M., Preda, N., "Hybrid Nanocomposite Thin Films for Photovoltaic Applications: A Review," *Nanomaterials*, Vol. 11, No. 5, pp. 1117, April 2021.
- ⁷¹Cassapakis, C. and Thomas, M., "Inflatable Structures Technology Development Overview," In Space Programs and Technologies Conference, American Institute of Aeronautics and Astronautics, Huntsville, AL, USA, 1995.
- ⁷²Stankiewicz, A., Szczygieł, I., and Szczygieł, B., "Self-healing coatings in anti-corrosion applications," *Journal of Materials Science*, Vol. 48, pp. 8041-8051, 2013.
- ⁷³Pelizzo, M. G., Corso, A. J., Tessarolo, E., Böttger, R., Hübner, R., Napolitani, E., Bazzan, M., Rancan, M., Armelao, L., Jark, W., Eichert, D., and Martucci, A., "Morphological and Functional Modifications of Optical Thin Films for Space Applications Irradiated with Low-Energy Helium Ions," *ACS Applied Materials and Interfaces*, Vol. 10, No. 40, pp. 34781-34791, 2018.

- ⁷⁴Dmitriyev, S., Koudrin, A., Labunets, A., and Kindrachuk, M., "Functional coatings application for strengthening and restoration of aviation products," *Aviation*, vol. 9, no. 4, pp. 39-45, 2005.
- ⁷⁵Lu, X., Zhang, C., Zhang, X., Cao, X., Kang, J., Sui, X., Hao, J., and Liu, W., "Dependence of mechanical and tribological performance on the microstructure of (CrAlTiNbV)_{Nx} high-entropy nitride coatings in aviation lubricant," *Ceramics International*, Vol. 47, No. 19, pp. 27342-27350, 2021.
- ⁷⁶Afshar, A., Mihut, D., Baqersad, J., and Hill, S., "Study of metallic thin films on epoxy matrix as protective barrier to ultraviolet radiation," *Surface and Coatings Technology*, Vol. 367, pp. 41-48, 2019.
- ⁷⁷Piscitelli, F., Chiariello, A., Dabkowski, D., Corrado, F., Marra, F., and di Palma, L., "Superhydrophobic Coatings as Anti-Icing Systems for Small Aircraft," *Aerospace*, Vol. 7, No. 1, article 2, pp. 1-15, 2020.
- ⁷⁸Bogaerts, A., Neyts, E. C., Guaitella, O., Murphy, A. B., "Foundations of Plasma Catalysis for Environmental Applications," *Plasma Sources Science and Technology*, Vol. 31, No. 5, pp. 053002, May 2022.
- ⁷⁹Zhang, J., Ricote, S., Hendriksen, P. V., and Chen, Y., "Advanced Materials for Thin-Film Solid Oxide Fuel Cells: Recent Progress and Challenges in Boosting the Device Performance at Low Temperatures," *Advanced Functional Materials*, Vol. 32, No. 22, pp. 2111205, May 2022.
- ⁸⁰Durán, I. R., Laroche, G. "Current Trends, Challenges, and Perspectives of Anti-Fogging Technology: Surface and Material Design, Fabrication Strategies, and Beyond," *Progress in Materials Science*, Vol. 99, pp. 106-186, 2019.
- ⁸¹Hatte, S., Pitchumani, R. "Analysis of Laminar Convective Heat Transfer Over Structured Non-Wetting Surfaces," *International Journal of Heat and Mass Transfer*, Vol. 167, pp. 120810, 2021.
- ⁸²Oh, J. K., Liu, S., Jones, M., Yegin, Y., Hao, L., Tolen, T. N., Nagabandi, N., Scholar, E. A., Castillo, A., Taylor, T. M., Cisneros-Zevallos, L., Akbulut, M. "Modification of Aluminum Surfaces with Superhydrophobic Nanotextures for Enhanced Food Safety and Hygiene," *Food Control*, Vol. 96, pp. 463-469, 2019.
- ⁸³Yang, H., Gao, Y., Qin, W., Sun, J., Huang, Z., Li, Y., Li, B., Sun, J. "A Robust Superhydrophobic Surface on AA3003 Aluminum Alloy with Intermetallic Phases In-Situ Pinning Effect for Corrosion Protection," *Journal of Alloys and Compounds*, Vol. 898, pp. 163038, 2022.
- ⁸⁴Costantini, R., Mollicone, J.-P., Battista, F. "Drag Reduction Induced by Superhydrophobic Surfaces in Turbulent Pipe Flow," *Physics of Fluids*, Vol. 30, No. 2, 025102, 2018.
- ⁸⁵Costa, C., Caiado, M., Tavares, C. J., Alves, E. S. "Sputtering-Deposited Thin Films on Textiles for Solar and Heat Managements: A Mini-Review", *Physica Status Solidi (A) - Applications and Materials Science*, Vol. 219, No. 3, 2100572, 2022.
- ⁸⁶Frota, M. M., Mattos, A. L. A., Miranda, K. W. E., Cheng, H. N., Biswas, A., Bastos, M. D. S. R. "Superhydrophobic Systems in Food Science and Technology: Concepts, Trends, Challenges, and Technological Innovations," *Applied Food Research*, Vol. 2, No. 2, 100213, 2022.
- ⁸⁷Wang, T., Zhao, Y. "Fabrication of Thermally and Mechanically Stable Superhydrophobic Coatings for Cellulose-Based Substrates with Natural and Edible Ingredients for Food Applications," *Food Hydrocolloids*, Vol. 120, pp. 106877, 2021.