Journal of Materials Science Research and Reviews

Volume 6, Issue 3, Page 238-247, 2023; Article no.JMSRR.99827

Beyond Waterproofing: Exploring the Emerging Frontiers of Superhydrophobic Coatings in Technology

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/99827

Review Article

Received: 23/03/2023
Accepted: 27/05/2023
Published: 08/06/2023

ABSTRACT

The unusual features and prospective uses of superhydrophobic coatings have garnered a lot of interest in recent years. These coatings possess the ability to repel water and other liquids, which makes them attractive for applications in anti-fouling, anti-icing, and self-cleaning surfaces. However, the adoption of these coatings in practical applications is still facing many challenges, such as durability, scalability, and cost-effectiveness. By examining the present state of the art in the area, this review paper seeks to investigate the requirements and difficulties of implementing superhydrophobic coatings in technology. It covers the recent advances in the fabrication of superhydrophobic coatings, their applications in different fields, and the existing limitations and future prospects. Finally, the review provides insights into possible solutions and strategies to overcome the challenges and realise the full potential of superhydrophobic coatings in technological applications. The potential applications of superhydrophobic coatings in the toy industry for

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developing waterproof and self-cleaning toys, as well as improving their durability, are an emerging and promising area of research.

Keywords: Superhydrophobic coatings; technology; anti-fouling; self-cleaning; challenges.

1. INTRODUCTION

Superhydrophobic coatings have emerged as a promising technology in recent years due to their unique ability to repel water and other liquids. These coatings have drawn significant attention from researchers and industries for their potential applications in various fields such as biomedical engineering, energy, electronics, aerospace, and marine engineering. In order to reject water droplets and stop liquid from sticking to the surface, superhydrophobic surfaces have exceptionally high water contact angles (>150 degrees) and low contact angle hysteresis (10 degrees) [1,2].

Chemical vapour deposition, physical vapour deposition, sol-gel processes, and micro/nanostructuring are only few of the ways that have been used to create superhydrophobic coatings [3]. Anti-fouling coatings, anti-icing coatings, and drag reduction in fluid flow are just a few of the many uses for which these coatings have proven effective. For instance, self-cleaning surfaces are achieved by combining superhydrophobicity with self-cleaning functionality, which allows the removal of dirt, dust, and other contaminants from the surface through the water droplets rolling off the surface.

Despite the tremendous potential of superhydrophobic coatings in technology, their adoption in practical applications is still facing many challenges. These challenges include durability, scalability, cost-effectiveness, and environmental impact [4]. The durability of the coatings is critical for their practical applications, but many of the current coatings suffer from poor stability and low resistance to wear and tear. Additionally, the scalability and cost-effectiveness of the coating fabrication process are also critical for their practical applications [5].

This review article aims to provide an overview of the needs and challenges of utilizing superhydrophobic coatings in technology. It discusses the recent advances in the fabrication of superhydrophobic coatings, their applications in different fields, and the existing limitations and future prospects [6]. Manoharan, K. et al. [7] provide insights into possible solutions and strategies to overcome the challenges and realize the full potential of superhydrophobic coatings in technological applications. The review will help to bridge the gap between the academic research and practical applications of superhydrophobic coatings and provide a comprehensive understanding of the current state-of-the-art in the field.

Due to their unusual qualities and wide range of possible technological applications, superhydrophobic coatings have been the subject of intensive study in recent years [8]. Self-cleaning surfaces, anti-fouling coatings, anti-icing surfaces, and reduced drag in fluid flow are just some of the many advantages that have been shown for these coatings. The fabrication of superhydrophobic coatings involves a combination of micro/nanostructuring techniques, surface modification, and chemical treatments.

The micro/nanostructuring techniques are used to create rough surfaces that have a high aspect ratio, which allows the air pockets to be trapped within the surface. The air pockets cause the liquid droplets to sit on top of the surface, forming a high contact angle and low contact angle hysteresis. Various techniques, such as lithography, laser ablation, and electrospinning, have been used to create the required surface structures.

Surface modification techniques, such as plasma treatment, chemical etching, and hydrothermal treatment, have been used to modify the surface chemistry of the substrates [9]. These treatments change the chemical composition of the substrate, creating a hydrophobic surface that repels water. Chemical treatments, such as silanization and fluorination, have also been used to modify the surface chemistry and create superhydrophobic surfaces.

Superhydrophobic coatings have found various applications in different fields such as biomedical engineering, energy, electronics, aerospace, and marine engineering. In biomedical engineering, superhydrophobic coatings have been used to develop anti-fouling and anti-bacterial coatings for medical implants, sensors, and other devices [10]. In energy applications, superhydrophobic coatings have been used to reduce the drag in fluid flow, which improves the efficiency of wind turbines and hydroelectric power plants.

In electronic applications, superhydrophobic coatings have been used to protect the electronic components from moisture and prevent water damage. In aerospace applications, superhydrophobic coatings have been used to prevent ice buildup on the aircraft surfaces, which improves safety and reduces fuel consumption [11]. In marine engineering, superhydrophobic coatings have been used to reduce the frictional resistance between the ship hull and seawater, which improves the fuel efficiency and reduces the emissions.

To overcome these challenges, researchers have been exploring various strategies, such as the use of new materials, coating techniques, and surface modification methods. For instance, the use of self-assembled monolayers (SAMs) has been shown to improve the durability and stability of the superhydrophobic coatings [12]. Similarly, the use of plasma treatment and nanocomposite coatings has been shown to improve the scalability and cost-effectiveness of the coating fabrication process.

Superhydrophobic surfaces are characterized by several parameters (properties/features) that define their ability to repel water droplets and minimize their adhesion to the surface. Some of the important parameters are:

- **Contact angle:** It is the angle at which the water droplet meets the surface. A higher contact angle indicates that the droplet is more spherical and has a greater tendency to roll off the surface.
- **Sliding angle:** It is the angle at which the droplet starts to slide off the surface. A lower sliding angle indicates that the droplet can slide off more easily and is less likely to stick to the surface.
- **Roughness:** The surface roughness of the substrate plays an important role in determining its superhydrophobic properties. A rougher surface with micro- and nano-scale features creates more air pockets that trap the water droplets and reduce their contact with the surface.
- **Chemical composition:** The chemical composition of the substrate (coatings) also affects its superhydrophobic properties. Surfaces with low surface energy materials such as fluoropolymers or silicones tend to be more superhydrophobic.
- **Durability:** The durability of the coating is an important parameter as it determines the longevity of the superhydrophobic properties. A superhydrophobic surface that is resistant to abrasion, chemical attack, and environmental factors will have a longer lifespan.

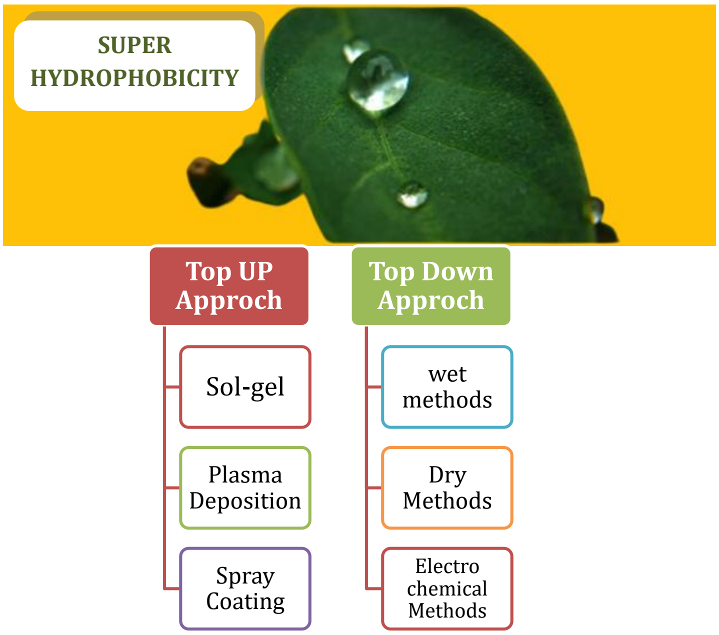

Image 1. Shows superhydrophobic materials cutting-edge making revolutionizing techniques

These parameters (properties/features)are often interdependent, and their optimization is critical for the development of effective superhydrophobic surfaces with desirable properties.

2. APPLICATIONS

Superhydrophobic surfaces have a wide range of potential applications due to their unique properties, which include water repellency, self-cleaning, anti-corrosion, anti-icing, and anti-fouling characteristics [7]. Here are some of the most promising applications of superhydrophobicity:

2.1 Self-Cleaning Surfaces

Superhydrophobic surfaces can be used to create self-cleaning surfaces for a variety of applications such as windows, solar panels, and textiles. The water droplets that fall on the surface do not spread out, but rather roll off, carrying with them any dirt or contaminants.

Self-cleaning surfaces are one of the most promising applications of superhydrophobicity. Superhydrophobic surfaces have a unique property known as the "Lotus Effect," named after the water-repelling properties of the lotus leaf. This effect arises from the combination of two factors: the roughness of the surface and its hydrophobic nature.

On a superhydrophobic surface, water droplets bead up into near-perfect spheres, minimizing the surface area of contact between the droplet and the surface. As the droplet rolls off the surface, it takes with it any dirt or contaminants that were present on the surface, effectively cleaning it.

Superhydrophobic surfaces, which can clean themselves, have several possible uses. For example, self-cleaning windows can reduce the need for frequent cleaning, saving time and money while maintaining the clarity of the windows [13]. Self-cleaning solar panels can improve their efficiency by keeping the surface free of dust and other contaminants. Self-cleaning textiles can be useful for outdoor clothing, reducing the need for frequent washing and increasing the lifespan of the clothing.

One of the key advantages of self-cleaning surfaces is that they can reduce the need for harsh cleaning chemicals. Traditional cleaning products can be harmful to the environment and may have health risks for humans. By reducing the need for these products, self-cleaning surfaces can be a more sustainable and environmentally friendly solution.

However, it's worth noting that the self-cleaning properties of superhydrophobic surfaces are not perfect. For example, the surfaces may not be effective at removing stains or stubborn dirt, and they may require periodic cleaning to maintain their effectiveness. Nevertheless, self-cleaning surfaces remain a promising application of superhydrophobicity with a range of potential benefits for various industries [14].

2.2 Anti-Corrosion Coatings

Superhydrophobic coatings can protect metal surfaces from corrosion by creating a barrier between the metal and the corrosive environment. The coating prevents water and other corrosive substances from coming into contact with the metal surface, thus reducing the rate of corrosion.

Anti-corrosion coatings are another important application of superhydrophobicity. Corrosion is a natural process that occurs when metal is exposed to water and oxygen, causing it to degrade over time. Corrosion can be a significant problem in various industries, such as construction, transportation, and marine engineering, leading to structural damage, reduced performance, and increased maintenance costs.

Superhydrophobic coatings can be used as an effective solution to prevent corrosion. By repelling water and other corrosive liquids, the coatings can protect metal surfaces from the moisture and oxygen that cause corrosion. Additionally, the coatings can create a barrier between the metal and the environment, reducing the contact area and slowing down the corrosion process.

Several studies have demonstrated the effectiveness of superhydrophobic coatings in preventing corrosion. For example, a study by da Silva, R. G. C. et al. [15] showed that a superhydrophobic coating applied to aluminum alloys reduced the corrosion rate by up to 91% compared to uncoated samples. Another study by Mohamed, A. M. A. et al. [16] showed that a superhydrophobic coating applied to steel sheets reduced the corrosion rate by up to 75%.

The anti-corrosion properties of superhydrophobic coatings have a range of potential applications. For example, they can be used to protect bridges, pipelines, and other infrastructure exposed to harsh environments. In the marine industry, they can be used to protect ships and offshore structures from the corrosive effects of seawater. In the aerospace industry, they can be used to protect aircraft components from corrosion caused by exposure to high altitude and extreme temperatures.

Overall, the use of superhydrophobic coatings as anti-corrosion solutions can offer significant benefits, including reduced maintenance costs, increased lifespan of metal structures, and improved safety and reliability. As research continues in this area, it's likely that more industries will adopt this technology to protect their metal assets.

2.3 Anti-Icing Surfaces

Superhydrophobic surfaces can prevent the formation of ice on surfaces by preventing water droplets from sticking to the surface. This property is particularly useful for applications in the aviation and transportation industry, where ice formation can be hazardous.

2.4 Anti-Fouling Surfaces

Superhydrophobic surfaces can be used to prevent fouling on surfaces such as ship hulls, pipelines, and medical devices. The surfaces prevent the adhesion of biofilms, bacteria, and other microorganisms, which can cause damage and contamination.

2.5 Drag Reduction

Superhydrophobic surfaces can reduce drag in fluid flow by minimizing the contact between the fluid and the surface. This property is particularly useful for applications in the transportation industry, where reducing drag can increase fuel efficiency.

Drag reduction is another important application of superhydrophobic surfaces. Drag is the force that opposes the motion of an object through a fluid, such as air or water. Reducing drag is essential in many industries, including aerospace, marine engineering, and transportation, as it can improve fuel efficiency and reduce emissions.

Superhydrophobic surfaces can reduce drag by creating a layer of air between the surface and the fluid, known as an air cushion [17]. This layer of air reduces the surface area of contact between the fluid and the surface, which in turn reduces the drag force. The roughness of the surface can also play a role in reducing drag by creating turbulence in the fluid flow, which can further reduce drag.

Several studies have demonstrated the potential of superhydrophobic surfaces for drag reduction. For example, a study by Wilson, M. [18] showed that superhydrophobic coatings applied to ship hulls reduced drag by up to 20% compared to conventional coatings. Another study by Piscitelli, F. et al. [19] showed that superhydrophobic coatings applied to aircraft wings reduced drag by up to 8%.

The potential benefits of drag reduction using superhydrophobic surfaces are significant. In the aerospace industry, drag reduction can lead to improved fuel efficiency and reduced emissions. In the marine industry, it can lead to improved speed and reduced fuel consumption. In the transportation industry, it can lead to improved fuel efficiency and reduced noise levels.

However, it's worth noting that the effectiveness of superhydrophobic surfaces for drag reduction can be influenced by various factors, such as the fluid flow conditions, surface roughness, and surface chemistry. As such, more research is needed to optimize the design of superhydrophobic surfaces for different applications and conditions.

Overall, the use of superhydrophobic surfaces for drag reduction is a promising area of research with potential benefits for various industries. As more research is conducted in this area, it's likely that more applications will emerge, and the technology will become more widely adopted.

2.6 Energy Harvesting

Superhydrophobic surfaces can be used to harvest energy from water droplets through a process called droplet-based energy harvesting [20]. The water droplets that fall on the surface generate an electrical charge that can be harnessed to produce electricity.

2.7 Medical Applications

Superhydrophobic surfaces can be used in medical devices such as catheters, stents, and implants [21]. These surfaces prevent the adhesion of biological fluids and cells, which can cause infections and other complications.

2.8 Electronic Devices

Superhydrophobic surfaces can be used in electronic devices to protect them from water damage. The surfaces can prevent water droplets from penetrating into the device, which can damage the electronics.

2.9 Oil-Water Separation

Superhydrophobic surfaces can be used to separate oil from water in industrial applications [22]. The surfaces prevent the mixing of the two liquids by repelling the water and attracting the oil.

2.10 Agriculture

Superhydrophobic coatings can be applied to plant leaves to prevent water droplets from sticking to the surface. This can reduce the risk of fungal and bacterial growth and improve the efficiency of pesticide application.

Superhydrophobic coatings also have potential applications in agriculture. In agriculture, water is essential for plant growth, but excessive water can cause damage to crops, particularly in low-lying areas where water can accumulate. Superhydrophobic coatings can help to prevent waterlogging and improve the efficiency of water usage in agriculture.

One way that superhydrophobic coatings can be used in agriculture is by coating plant leaves with a superhydrophobic layer [23]. This layer can repel water droplets, preventing them from clinging to the leaves and reducing the risk of damage or disease caused by excess moisture. Additionally, superhydrophobic coatings can be applied to soil surfaces to create a water-repellent layer, reducing the amount of water needed for irrigation and preventing waterlogging.

Several studies have demonstrated the potential benefits of superhydrophobic coatings in agriculture. For example, a study by Frota, M. M. et al. [24] showed that superhydrophobic coatings applied to tomato leaves reduced the adhesion of water droplets by up to 90%, which led to a reduction in disease incidence and an increase in yield [25]. Another study by Adair Gallo Jr. et al. [26] showed that superhydrophobic coatings applied to soil reduced the amount of irrigation water needed by up to 30%.

The use of superhydrophobic coatings in agriculture has several potential benefits, including improved crop yield, reduced water usage, and improved resistance to disease and pests. Additionally, superhydrophobic coatings can help to reduce the amount of pesticides and fertilizers needed for crop production, as they can prevent them from being washed away by rain or irrigation.

Overall, the use of superhydrophobic coatings in agriculture is a promising area of research, with potential applications in crop protection, irrigation, and sustainable agriculture. As more research is conducted in this area, it's likely that more applications will emerge, and the technology will become more widely adopted in the agricultural industry.

2.11 Food Packaging

Superhydrophobic surfaces can be used in food packaging to prevent moisture from entering the packaging and spoiling the food. The surfaces can also prevent the adhesion of bacteria and other contaminants.

2.12 Textiles

Superhydrophobic coatings can be applied to textiles to create water-repellent fabrics [27]. This can be useful for outdoor clothing, camping gear, and other applications where water resistance is important.

These applications demonstrate the diverse range of uses for superhydrophobic surfaces in various industries. With continued research and development, the potential applications of superhydrophobic coatings will only continue to grow.

Superhydrophobic coatings have potential applications in the toy industry as well. One application is in the development of waterproof toys that can be used in water, such as swimming pools or bathtubs. By coating the toys with a superhydrophobic material, the toys can be made to repel water and stay dry, reducing the risk of water damage or corrosion.

Another potential application is in the development of self-cleaning toys. Children's toys are often exposed to dirt, grime, and other contaminants, which can make them unhygienic and potentially dangerous for children to play with. By coating toys with a superhydrophobic material, the toys can be made to repel dirt and other contaminants, making them easier to clean and more hygienic.

Furthermore, superhydrophobic coatings can also be used to improve the durability of toys. Toys that are frequently played with, thrown, or dropped can be susceptible to wear and tear, which can reduce their lifespan. By coating toys with a superhydrophobic material, they can be made more resistant to scratches, dents, and other forms of damage.

Overall, superhydrophobic coatings have potential applications in the toy industry for developing waterproof toys, self-cleaning toys, and improving the durability of toys. As the technology continues to develop and become more affordable, it is likely that we will see an increasing number of toys incorporating superhydrophobic coatings in the future.

3. CHALLENGES

Despite the many potential applications of superhydrophobic coatings, there are several challenges that must be overcome to realize their full potential.

One of the main challenges is durability. Superhydrophobic coatings are susceptible to wear and degradation, particularly in harsh environments or when exposed to UV radiation [28]. Over time, the superhydrophobic properties of the coating can degrade, reducing its effectiveness. Improving the durability of superhydrophobic coatings is therefore a major challenge in the field, and researchers are exploring ways to develop more robust coatings that can withstand harsh environments.

Another challenge is scalability. While superhydrophobic coatings have been demonstrated in the lab, scaling up the production of these coatings to an industrial level can be difficult [29]. In many cases, the production methods used in the lab are not suitable for large-scale manufacturing, and new methods must be developed. Additionally, the cost of producing superhydrophobic coatings can be high, which limits their commercial viability.

Another challenge is the complexity of the surface topography required to create superhydrophobic surfaces. The surface must be rough at the nanoscale, which can be difficult and expensive to achieve using conventional manufacturing methods. Additionally, the roughness of the surface must be carefully controlled to optimize the superhydrophobic properties of the coating. Developing cost-effective and scalable methods for creating the required surface topography is therefore a major challenge in the field.

Finally, there are challenges associated with the integration of superhydrophobic coatings into existing products and systems. For example, in the aerospace industry, superhydrophobic coatings must be compatible with existing coatings and materials used in aircraft manufacturing [30]. Additionally, in the agriculture industry, superhydrophobic coatings must be compatible with existing irrigation systems and soil types. Developing coatings that are compatible with existing systems and materials is therefore an important challenge in the field.

Despite the challenges associated with superhydrophobic coatings, there are many opportunities for future research and development in this field.

One potential area of research is the development of new materials and coatings that are more durable and robust. This could involve the use of new materials, such as graphene or carbon nanotubes, or the development of new coatings that can better withstand harsh environments.

Another area of research is the integration of superhydrophobic coatings into new applications and industries. For example, superhydrophobic coatings could be used to improve the efficiency of desalination processes, or to create self-cleaning windows for buildings. As new applications are discovered, the demand for superhydrophobic coatings is likely to increase, creating new opportunities for research and development.

Additionally, there is significant potential for collaboration between researchers in different fields, such as materials science, chemistry, and engineering. By working together, researchers can develop new approaches to creating superhydrophobic coatings and overcome some of the challenges associated with this technology.

Finally, there is significant potential for the commercialization of superhydrophobic coatings. As the technology becomes more widely adopted, the cost of production is likely to decrease, making it more affordable for commercial applications. Additionally, the use of superhydrophobic coatings in industries such as aerospace and agriculture could lead to significant cost savings and improved efficiency.

Overall, while there are challenges associated with superhydrophobic coatings, there are also many opportunities for future research and development in this field. As new materials and applications are discovered, the potential for superhydrophobic coatings is likely to continue to expand.

4. CONCLUSION

In conclusion, superhydrophobic coatings have a wide range of potential applications in various industries, including the toy industry. The use of superhydrophobic coatings in toys can improve their durability, hygiene, and resistance to water damage. Superhydrophobic coatings are anticipated to appear on more and more toys as the technology improves and costs decrease. With its promising applications, superhydrophobic technology has the potential to revolutionize the toy industry, leading to the development of new and innovative toys that are more durable, hygienic, and fun for children to play with.Furthermore, the use of superhydrophobic coatings in toys can also enhance their safety. By making toys more resistant to water damage, they can reduce the risk of electrocution, which is a common safety concern with electronic toys. Additionally, by making toys more hygienic, superhydrophobic coatings can reduce the risk of bacterial and viral infections, which is especially important for young children who are more susceptible to illnesses.Moreover, the use of superhydrophobic coatings in toys can also have a positive impact on the environment. By making toys more durable and resistant to damage, they can reduce the need for frequent replacements, which in turn can reduce waste and the environmental impact of toy manufacturing.The toy business stands to gain much from the increased use of superhydrophobic coatings due to their many potential advantages. Superhydrophobic coatings have a number of potential uses in children's toys, including increasing their safety, longevity, and enjoyment while they play.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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