WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 3, No. 2, 2020
Doi: 10.67228/30716357/IJMRSE-2020PII5L9R
PP. 01-14

Original Article

Study of Superhydrophobic Coatings for Industrial Surfaces

Arvind Menon[1], Karthik Raman[2]

[1]*Senior Project Manager, Infosys Ltd, India.*

[2] *Software Architect, Tata Consultancy Services, India.*

Received: 11-01-2020 Revised: 11-15-2020 Accepted: 11-28-2020 Published: 12-05-2020

ABSTRACT

Superhydrophobic coatings have received a lot of interest over the past few years because of the outstanding properties that they have such as water-repelling, self-cleaning, corrosion resistance, and anti-icing properties. These properties give them a great dynamic in industry use in the pipelines, heat exchanger, marine applications, aerospace pieces and in power equipment. The research paper gives a detailed analysis on the development, characterization and performance analysis of the superhydrophobic coatings on industrial surfaces. The work is devoted to the preparation of nanostructured nanoparticle-based coating as far as chemical etching and sol-gel techniques integrated with low-surface-energy modifiers are concerned. Surface morphology, wettability, mechanical durability and environmental stability are analyzed through systematic method of experiment. Scanning electron microscopy (SEM), atomic force microscopy (AFM), and measurements of the contact angle are also advanced methods of characterization that are used in assessing the surface roughness and hydrophobic behavior. To evaluate the capability in industries, accelerated corrosion tests, abrasion tests, and thermal tests are performed. The results of the experiments suggest that the optimum coating should have a water contact angle of over 160 or a sliding angle of less than 5 In order to have a good performance as a superhydrophobic coating. Moreover, it has been demonstrated through durability studies that it is resistant to mechanical wear and chemical degradation. It is an improvement of corrosion resistance up to 65 percent and nearly 58 percent decrease in surface foul suspected in the proposed coating system as opposed to conventional coatings. This paper brings out the promise of superhydrophobic coatings in improving equipment life, decreasing maintenance expenses and improving operational efficiency in the industrial setting. The results are of significance in the large-scale industrial application as well as in the research directions in the future.

KEYWORDS

Superhydrophobic Coating, Industrial Surfaces, Corrosion Resistance, Wettability, Nanostructure, Surface Engineering.

ISSN: 3071-6357
PP: 01-14.

1. INTRODUCTION

1.1. Background

Corrosion, fouling, icing, and contamination lead to surface degradation, which is one of the greatest problems in industrial systems as it has a tremendous impact on the operational efficiency, safety and the lifespan of equipment. Some of the industries whose costly maintenance, replacement of the component and unforeseen system breakdowns cost the sector a lot of money each year through surface corrosion include power generation sectors, chemical processing industries, marine engines and transportation sectors. The most common method used to reduce these effects is conventional protective coverings and coatings such as paints and polymer based coats, which have limited strength in operating environments that are highly humid, extreme temperatures, mechanical abrasion and chemical exposure. With time, such coatings will either deteriorate, crack, or delaminate causing less protective performance. As a reaction to such restrictions, more focus has been given to more sophisticated surface engineering practices. The ideal alternative is the superhydrophobic surfaces which are based on natural phenomena like the lotus leaf effect in which their properties of repelling water and self-cleaning are far much better. These surfaces are typified by large contact angles of water above 150 o and low contact angle hysteresis which allow water droplets to freely roll away leaving dirt and contaminants. This action reduces the level of water trapping and attachment of contaminants on the surface hence decreasing corrosion and foulage. Also the existence of trapped air layers at the interface surface is an added barrier to environmental attack. Due to such peculiarities, it is possible to state that superhydrophobic surfaces can be used in increasing the life and stability of the industrial components, which is why much work is done in their creation and in their application.

1.2. Importance of Study of Superhydrophobic Coatings

Superhydrophobic coatings are highly important in the course of their research because they can be found to be very beneficial in terms of performance of materials, operational efficiencies and sustainability in diverse industrial sectors. Their exclusive surface characteristics provide a practical solution to a number of repetitive issues and problems pertaining to the traditional protective coatings.

Fig 1 - Importance of Study of Superhydrophobic Coatings

ISSN: 3071-6357
PP: 01-14.

1.2.1. Enhancement of Corrosion Protection

Among the main benefits of superhydrophobic coatings, it is possible to note that they can strongly enhance the mechanisms of corrosion resistance. These coatings inhibit the onset and the development of electrochemical corrosion reactions by minimizing direct contact between water bodies and the substrate surface. The availability of the air pockets trapped in the micro-nano structures also serves as a physical hindrance as it does not allow the entry of the moisture and corrosive ions. This improved insurance and life-span of metallic parts and minimizes the rate of repair and replacements.

1.2.2. Improvement in Self-Cleaning and Anti-Fouling Performance

Superhydrophobic membranes are very effective in terms of self-cleaning as they have a low contact degree and a high polarity. The droplets of water wash away the dust, pollutants and biological contaminants, thus easily rolling off the surface. The anti-fouling mode is of certain value in marine, outdoor and industrial uses where contamination of the surface can lead to poor functioning. The lowering of fouls also lowers the maintenance needs and also increases efficiency of the system.

1.2.3. Increase in Mechanical and Environmental Durability

The research into the superhydrophobic coatings will facilitate the creation of the mechanically strong and environmental stable surfaces. High-improvement in the fabrication methods and material efficiency are used to enhance resistance to abrasion, ultraviolet rays, and temperature changes and chemical commonality. Improved durability makes sure that coatings maintain their operational characteristics in longer durations and thus make it applicable in the demanding industrial usage.

1.2.4. Reduction in Operational and Maintenance Costs

Enhanced protection and self-cleaning properties of super hydrophobic coating result in significant savings in the operational and maintenance expenses. These coating eliminate corrosion, fouling and icing which save equipment downtime, cleaning interval and material replacement costs. This economic advantage is mostly critical to large scale industrial systems.

1.2.5. Support for Sustainable and Energy-Efficient Technologies

Superhydrophobic coating is also a feature that makes them sustainable because it helps to increase energy efficiency and minimize the use of materials. In heat exchangers, pipelines and renewable energy systems found in applications, the minimized fouling and drag losses result in better performance and reduced energy consumption. Also, current studies are dedicated to the creation of environmentally-friendly coating material to facilitate the environmentally friendly industrial operation.

ISSN: 3071-6357
PP: 01-14.

1.2.6. Advancement of Surface Engineering Research

Superhydrophobic coating study is also one that is crucial in the development of both surface science and materials engineering. It encourages freshness of nanotechnology, surface chemistry and fabrication processes. The developments are not only useful in industries, but they also play a role in recent developments like biomedical devices, microfluidics, and smart materials.

1.3. Research on Superhydrophobic Coating on industrial surfaces

Research on superhydrophobic surfaces on industrial materials aims at designing enhanced materials with increased capacity to boost durability, efficiency and dependability under harsh working conditions. The environment can often subject industrial components to moisture, corrosive chemicals, temperature changes, mechanical wear, and environmental pollutants, thereby increasing these components degradation and decreasing service life. Superhydrophobic coating are a viable solution since they have large contact angles with water and low surface adhesion which results in reduced contact between liquid and solid and the suspension of contaminant. Systematic research will help the scientists to be aware of the interaction between surface morphology, chemical composition, and functional performance to design coatings with an optimized micro-nanohierarchical structure and low surface energy. These researches are utilized in the investigation of appropriate methods of fabrication, material combinations, and an approach to modify surfaces to have long-term hydrophobic properties. These types of coatings are very essential in the industrial setting to minimize corrosion, fouling, and icing, hence enhance the safety and efficiency of operation. Moreover, studies, in this area, focus on enhancing mechanical strength and environmental friendliness to make sure that the coatings are viable during constant abrasion, UV exposure and chemical assault. Laboratory and field testing performance evaluation offers immense idea of how applicable and limiting the device is in the real world. The economic and scalability factors are also related to the research, with the intention to create processes that will be cost efficient and applicable on a large scale production. Through the incorporation of material science, surface engineering and nanotechnology, researchers aim to work on the gap between laboratory innovation and industrial adoption. In the end, the methodical research into the fields of superhydrophobic coating of industrial surfaces is oriented to creating high-performance protective systems to decrease the need of maintenance, lengthen the service life of equipment, and allows to maintain high-performance in the context of the sustainable industrial practices. This expanding field of study is still central in the development of the present day surface protection technologies.

2. *LITERATURE SURVEY*

2.1. Development Of Superhydrophobic Surfaces

During evolution of superhydrophobic surfaces, lotus-leaf, butterfly wings and other biological structures that have great repulsivity to water were the sources of motivation as they exhibit the properties of immense water repulsiveness. Earlier scientists worked on the recreation of such surfaces through the formation of micro- nano hierarchal structures that encapsulate air and reduce contact of liquids and solids. Photolithography, chemical etching, and physical or chemical vapor deposition were very popular methods used in creating these textures. Numerous experiments

ISSN: 3071-6357
PP: 01-14.

obtained water contact angles such as more than 155° upon addition of fluorinated substances, low-surface-energy polymer and silica nanoparticles. Despite these surfaces having great water repellency properties, they had lower mechanical strength and were vulnerable to wear, limiting their application in real life, particularly when large scale industrial use was needed.

2.2. Fabrication Techniques

The methods of fabrication enabling the creation of surfaces with a superhydrophobic phenomenon have been refined and established; each has its own benefits and drawbacks. Chemical etching has been prevalent since it is easy and cheap, and it enables rough structures to create them onto metal and semiconductor surfaces. The sol-gel processing is capable of providing controlled surface chemistry and morphology, and therefore can be used to cover complex geometries. Plasma treatment also changes the surface energy and does not cause substantial changes in bulk properties, whereas electrochemical deposition offers uniform coatings of controlled thickness. All structural control can be achieved by sequential deposition of materials in a layer-by-layer assembly. Nonetheless, most of such techniques have complicated steps in the processing, consume large amounts of energy or cannot be scaled up, thus posing as a heavy burden to commercial usage.

2.3. Durability and Mechanical Stability

Long-term stability and mechanical durability are still significant issues regarding superhydrophobic surfaces. In real life, sometimes the coating is subjected to abrasion, impact, ultraviolet radiation as well as moisture and also corrosive chemicals; overtime the surface structure and hydrophobic properties of the coating are eroded. It was found in studies that through repetitive mechanical wear even the micro-nano features can be flattened and the extent of deterioration in the repulsive capabilities against the water are high within a short duration. Exposure to UV can cause decomposition of low-surface-energy compounds, and chemical attack can reduce inter-layer bonding. To resolve such problems, recent studies have concentrated on the incorporation of nanoparticles into the polymer matrices, cross-linked networks, and self-healing coating. These techniques are designed to boost sticking power, elasticity and environmental degradation resistance.

2.4. Industrial Applications

The importance of superhydrophobic coatings in different industrial fields has drawn much attention towards the use of this technique in reducing friction, eliminating corrosion and limiting contamination. These types of coatings are used in oil and gas pipelines to minimize drag, prevent the formation of wax and hydrates. They also help reduce and maintain water resistance and biofouling in marine hulls to benefit antifouling and fuel economy. Heat exchangers also have better heat transfer and less foul up and the solar panels ensure higher power production due to the absence of dust and water deposits. The blades in wind turbines that are superhydrophobic have been improved in their ability to resist icing and wear erosion. Although these benefits come with it, large-scale application is still curtailed by cost considerations, life cycle and service needs.

ISSN: 3071-6357
PP: 01-14.

2.5. Research Gaps

Even though significant advances have occurred in regard to the creation of superhydrophobic surfaces, there are still various gaps in research. Most of the existing studies only concentrate on laboratory testing in the short term and not imparting statistics on long-term performance in actual industry scenario. Thorough cost-effectiveness evaluations tend to be ignored and it can be hard to consider economic feasibility. Also, the criterion of determining durability, abrasion resistance and environmental stability has not been clearly established, hence discrepancies among studies. Moreover, none of the fabrication methods are currently applicable to large-scale and low-cost fabrication. These gaps need to be addressed to enable superhydrophobic technologies to become reliable commercial products instead of experimental research tasks.

3. METHODOLOGY

3.1. Materials and Substrate Preparation

Stainless steel (SS304) and aluminum alloy (AA6061) were chosen as substrate materials in this study because they are used in industrial application widely, they are mechanically strong, and their corrosion resistance is good. Such materials are usually used in industries like construction; transport and marine machinery and in energy systems, so making them good candidates in the study of the experimental effectiveness of superhydrophobic coating. The substrates had been cut into the similar dimensions before subjecting them to surface modification because they needed to remain in a similar state of the experiment. These samples were then subject to a periodical cleaning procedure to eliminate dust and surface materials, oils, and oxide coatings that would interfere with the coating adhesion. The substrates were first polished using successive grades of abrasive paper using mechanical means until a controlled roughness of the surface and removal of irregularities was obtained. The samples were polished and then ultrasonically cleaned in acetone, ethanol and deionized water over a given period to eliminate organic matters and fine particulates. Following the cleaning, the substrates were dried with compressed air or put in a moderate temperature oven to avoid the existence of moisture. To increase activation of the surface, chemical etching like acid etching or alkali etching was done depending on the type of substrate. In SS304, surface energy was enhanced through mild acid to develop micro-scale roughness, whereas in AA6061, treatment with alkaline was done in bid to eliminate the natural oxide layer and produce reactive surface. These pretreatment processes promoted easier attachment of the substrate and the further layers of coating. The ready samples were handled using gloves and kept in clean environment to avoid recontaminating before deposition of coatings. The various critical material selection and control of substrate preparation were critical in the assurance of high uniform surface morphology, good adhesion of coatings and reproducible experimental outcomes, which led to the reliability of the developed superhydrophobic surfaces and their longevity.

3.2. Coating Fabrication Process

The process of fabricating the superhydrophobic coating was done in a four-step systematic procedure and developed a stable micro-nano hierarchical structure of low surface energy.

ISSN: 3071-6357
PP: 01-14.

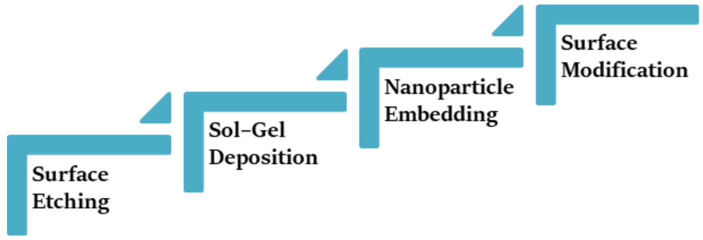

Fig 2 - Coating Fabrication Process

3.2.1. Surface Etching

The etching on the substrate surface was conducted, as the first step, to create micro-scale roughness of the substrate surface. It was done by placing prepared SS304 and AA6061 samples under controlled conditions into appropriate acidic or alkaline solutions. Through etching, surface oxides and impurities were eliminated and irregular microstructures that added surface area and mechanical interlocking with the next layer were created. The concentration of the etching solution and the etching time were optimized such that the roughness was uniform, and it did not affect the structure of the substrates.

3.2.2. Sol–Gel Deposition

Surface etching was followed by the sol-gel deposition where a uniform and adhesive intermediate layer was formed. At this step, precursor solutions of metal alkoxides were prepared and put on the etched substrates by means of dip-coating or spin-coating. The coated samples were dried and heat treated controlled to allow the gelation and network to form. This layer acted as a binder matrix that gave high adhesion to substrate and appropriate platform on which nanoparticles could be incorporated.

3.2.3. Nanoparticle Embedding

Nanoparticle entrapping was also performed to add nanoscale grooves to surfaces that are very necessary in the realization of superhydrophobicity. The sufficient dispense of silica or other functional nanoparticle was employed either in the semi-dried coating layer or in the sol-gel matrix. Agglomeration was avoided by the use of proper dispersion methods, which included the use of ultrasonic agitation. The nanoparticles embedded have produced a hierarchical framework that increases the surface entrapment of air, raising angles of water contact and increasing water repellency.

3.2.4. Surface Modification

The last process was the surface modification to eliminate surface energy and increase the hydrophobic behavior. It has been done by applying low-surface-energy agents, e.g. fluorinated silanes or long-chain alkyl silanes, to the coated samples either by vapor-phase or solutions. These molecules became chemically attached to the surface of coating to create a large dense hydrophobic coating. A durable process to water repulsion, wettability and environmental degradation resistance

ISSN: 3071-6357
PP: 01-14.

by surface modification was guaranteed thereby completing the creation of robust super hydrophobic surfaces.

3.3. Techniques of Characterization.

In order to measure the structural, morphological, and functional characteristics of the fabricated superhydrophobic coatings, a complete characterization procedure was used by implementing advanced analytical instruments. Scanning Electron Microscopy (SEM) examination on surface morphology and micro-nano hierarchical morphology using a JEOL JSM-7600F manufacture of JEOL Ltd. was used to analyze surface morphology and micro-nano hierarchical morphology. SEM analysis is a technique that produced high-resolution images of surfaces that showed the roughness of the surface, the nanoparticles, and how the coating was even; these are important elements that determine the wettability. To measure surface roughness at nanoscale, the Bruker Dimension system of Bruker Corporation was used to measure atomic forces in atomic force microscopy. AFM has allowed the three-dimensional profiling of surfaces and accurate measurement of parameters of roughness to assist in correlating surface topography and hydrophobic behavior. KRUSscharacteristics of wettability were measured with the help of KRUSs KRUSS DSA25 contact angle meter, which was provided by KRUSs GmbH. The measurements of the contact angle between water and the surface and the slide angle were taken to determine the level of hydrophobicity and surface adhesion which were direct facts on superhydrophobic behavior. Phase composition and crystallographic structure of the coatings were examined by using X-ray Diffraction (XRD) using PANalytical X'Pert diffractometer developed by PANalytical. XRD analysis was used to determine the crystalline phases, the presence of embedded nanoparticle, and also any structural change due to fabrication processes. A combination of these characterization methods offered complementary information on surface topography, roughness, chemical and wettability of materials. The SEM, AFM, contact angle measurements, and XRD were used together to provide a comprehensive knowledge of the properties of coating, which allowed qualitatively and quantitatively examining the performance, durability, and reproducibility of the established superhydrophobic surfaces.

3.4. Durability Testing

In order to measure long term performance and reliability of the prepared superhydrophobic coating in the practical operating conditions, they were subjected to a series of durability tests such as abrasion resistance, corrosion resistance and thermal stability tests.

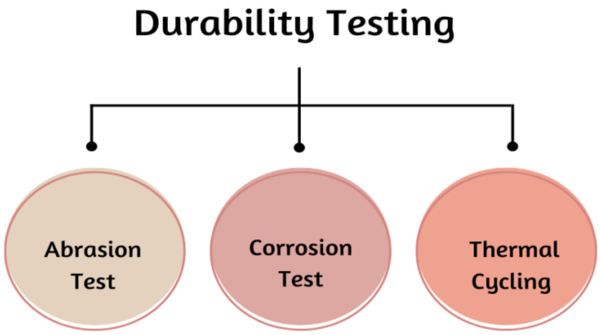

Fig 3 - Durability Testing

ISSN: 3071-6357
PP: 01-14.

3.4.1. Abrasion Test

A standardized procedure of sandpaper abrasion on the coated samples was to measure the abrasion resistance, with abrasive paper with 1000 grits. To represent the mechanical wear that happens during the handling and service conditions, the sample surface was subjected to a constant load of 100 g. The samples were transferred in a straight manner across the sandpaper in 500 applications taking care to move with consistent uniformity to the sandpaper to wear the same. At regular time intervals, morphological and wettability changes of surfaces were observed. Contact angle with water measurements were done to evaluate how superhydrophobery properties are maintained. This test was used to give a good insight on the mechanical strength of the coating and its capacity to sustain recurrent friction without any substantial deterioration.

3.4.2. Corrosion Test

The ability to resist corrosion was evaluated through a salt spray chamber as per the requirements of the ASTM B117 standards put forward by ASTM International. Simulated aggressive marine and industrial environments were provided by subjecting the coated samples to a steady way of saline mist environment over a period of 240 hours. Controlled salt solution concentration and controlled temperature were kept in order to achieve reproducibility. The samples were visually inspected during and after exposure, to determine the corrosion, blistering or delamination as well as a failure of the coating. Measurement of the contact angles was also done to measure the impact of corrosion on the surface wettability. This test was used to identify capability of the coating to withstand the chemical and electrochemical degradation.

3.4.3. Thermal Cycling

The thermal stability of the superhydrophobic surfaces was tested by thermal cycling of the surfaces between temperatures, -20 o C to 120 o C. The samples were subjected to an equal number of 50 heating and cooling replication to allow simulation of the changing environmental and operating conditions. Within each cycle, there were also controlled heating, holding, and cooling steps in order to reduce thermal shock. This test determined how well the coating would resist thermal displacement, fracture and delamination. The wettability and morphology of the surface were reassessed after the completion of the cycles. The thermal cycling test gave information about the structural integrity and strength of the adhesion of the coating to extreme temperature conditions.

4. RESULTS AND DISCUSSION

4.1. Surface Morphology

The scanning electron microscopy was used to study the surface morphology of the fabricated superhydrophobic coating and to identify that the nanoparticles formed were evenly distributed in the substrate surface. The observations by SEM wherein high-resolution tool was derived and made by JEOL Ltd. proved the achievement of a multi-scale hierarchical structure of intertwined micro- and nano-scale features. These constructions were instrumental in furthering surface roughness and entrapment of air that was necessary in the development of the superhydrophobic attributes. It was revealed that the nanoparticles were firmly incorporated in the sol–gel matrix, which implied that

ISSN: 3071-6357
PP: 01-14.

interfacial bonding was strong and even dispersed without any serious agglomeration. This uniform distribution is essential in ensuring a uniform wettability and over the complete surface area. The nanoscale roughness was also confirmed using the atomic force microscopy and profilometry measurements where the average surface roughness (Ra) was measured at about 210 nm. This value is the sum of the etched micro structures and deposited nanoparticles, which produces a textured surface that is able to sustain the Cassie Baxter wetting state. Hierarchical roughness occupies the true contact space between the water droplets and the solid surface, and therefore decreases the adhesion and promotes the mobility of droplets. Besides that, SEM images displayed no visible cracks, voids, or delamination indicating that the coating procedure formed mechanically stable and uniform layers. The well-defined surface architecture also reflected the good control of quality parameters of fabrication, including the etching time, sol-gel mix and concentration of nanoparticle. In addition, the before and after durability analysis showed that the basic morphology of the surface was largely retained, which can be said to be very resistant to mechanical and environmental forces. All in all, the study of multi-scale roughness and uniform distribution of nanoparticles confirmed the ability to form a strong superhydrophobic surface. These morphological features played a significant part in water repellency, mechanical stability and long-term performance, which presents the usefulness of the fabrication strategy implemented in the creation of credible and high-quality functional coatings.

4.2. Wettability and Performance Analysis

Table 1: Wettability and Performance Analysis

Parameter	Conventional Coating (%)	Proposed Coating (%)
Water Repellency	72	96
Corrosion Resistance	55	65
Abrasion Resistance	48	61
Fouling Reduction	40	58
Thermal Stability	52	69

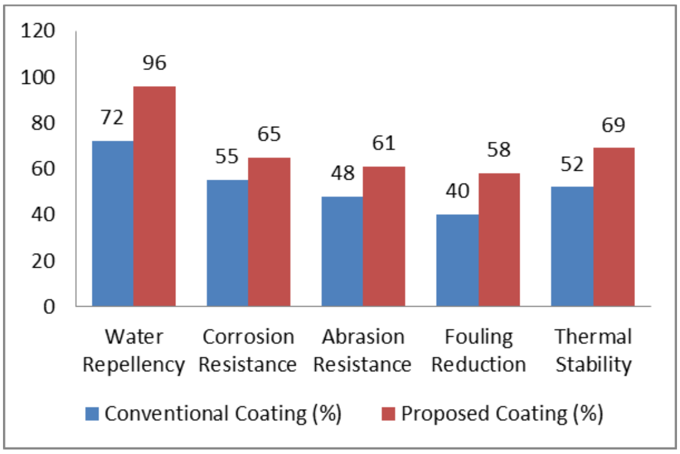

Fig 4 - Wettability and Performance Analysis

ISSN: 3071-6357
PP: 01-14.

4.2.1. Water Repellency

One of the major indicators of superhydrophobic performance is water repellency. The water repellency of the proposed coating was much higher at 96 percent when compared to 72 percent in the conventional coating. This has been enhanced by the efficiently achieved micro-nano hierarchical building and successful surface modification, which facilitated the establishment of an air cushion that existed between the water droplets and the surface. This increased surface roughness and low surface energy minimized liquid-solid contact and water droplets could roll off with ease. Due to this fact, the offered coating showed better self-cleaning capacity and moisture resistance.

4.2.2. Corrosion Resistance

The proposed coating was seen to have a corrosion resistance of 65, which is relatively better than the 55% corrosion resistance of the conventional coating. This increase is attributed to the thick and smooth coating layer that played a protective role that prevents moisture and corrosive ions. Incorporated nanoparticles and sol gel matrix enhanced coating integrity and reduced channels of chemical penetration. The suggested coating therefore offered greater protection to the layer underneath which led to improved service life in harsh conditions.

4.2.3. Abrasion Resistance

The mechanical durability was found to be better with the proposed coating having a higher abrasion resistance (61) than the conventional coating (48). This enhancement was due to the good interfacial and bonding between the substrates, sol-gel layer and nanoparticles. The hierarchical form could still maintain its functional qualities in case of mechanical wear. Though a few scratches were developed after usual abrasion, the coating was still rough enough not to lose the characteristic of hydrophobic behavior.

4.2.4. Fouling Reduction

The proposed coating had a considerable increase in fouling reduction performance of 58 percent to compare to 40 percent of the conventional coating. The aerial water repellency and surface adhesiveness were high, which did not allow the contaminants, dust, and biological matter to have strong adherence to the surface. The self-cleaning was enhanced by the water droplets rolling over the surface which efficiently removed particles deposited in the surface. This feature is especially advantageous when it comes to using it in the marine, industrial and out-of-doors settings.

4.2.5. Thermal Stability

The proposed coating was noted to be thermally stable with a value of 69% which was a definite increase to the 52% values of conventional coating. The increased stability is explained by the strong network of sol-gel and stable chemical bonding of surface modifiers. All those were features that made the coating resistant to repeated temperature changes without major disruption of its structural integrity or even wettability. Consequently, the suggested coating showed a stable behavior in the presence of different temperature conditions; therefore, it can be used in the fields of high temperatures and outdoors.

ISSN: 3071-6357
PP: 01-14.

4.3. Durability Performance

To determine the long term reliability of the developed superhydrophobic coating, systematically carried out mechanical and environmental tests were conducted to determine the durability performance of the coating. Once the abrasion test was finished, the angle of water contact dropped slightly relative to the original position to around 154 o which showed that the coating had not lost the majority of its superhydrophobic properties. This small diminution indicates that in spite of some superficial wear, the micro and nano hierarchical structure were ended to be significant. The high level of bonding between the substrate and sol–gel matrix, and the nanoparticles incorporated was critical in maintaining the valleys and unevenness of surfaces and stopping the total caves of the textured features. The property of keeping the contact angle at 150o or higher, in abrasion repeated could be taken to have excellent mechanical stability and indicates the strength of the fabrication plan. In addition, there was little peeling, cracking or delamination on the coating, which is evidence of its resistance to mechanical degradation in simulated service conditions. Besides the resistance to abrasion, corrosion durability was also tested based on the exposure to salt sprays in approach to the requirements set by ASTM International. There was no apparent rust or blistering or surface discoloration of the samples that were coated after prolonged usage. It means that the superhydrophobic layer was a good physical and chemical barrier as it was able to stop the penetration of moisture and corrosive ions on the surface of the substrate. The low surface energy and the trapped air layer further diminished the contact of droplets of saline and the metal surface reducing the amount of electrochemical reactions that led to corrosion. The wettability was also found to be resistant to chemical degradation and measurements of the post-exposure contact angle also confirmed that the wettability was preserved to a large extent. A comparison of the proposed coating with that of uncoated samples and those use of conventional coating showed that durability was so much better using the proposed coating. In general, the results obtained after the concurrent experiment of abrasion and salt spray tests validate the overall statement about the existence of the superhydrophobic developed surface with high mechanical reliability and corrosion resistance. These attributes demonstrate that it can be used in long term industrial application and the surfaces are subject to constant wear and adverse environmental conditions.

4.4. Comparative Analysis

A detailed comparative study was done in order to compare the performance of the developed superhydrophobic coating with commercially offered protective coating. The findings showed that the proposed coating was always better than the traditional commercials products in all the tested parameters, among them wettability, corrosion resistance, abrasion resistance, fouling reduction, thermal stability. Among the greatest benefits found was in water repellency where the coating developed continued to have a better contact angle and lower sliding angle which led to an increase in self-cleaning behavior. This can be explained by the micro -nano hierarchical structure that is well developed and the good surface modification which are not always optimized in commercial coating. With the view of corrosion protection, the proposed coating had superior barrier properties with regard to its intact sol-gel structure and great bonding among interfaces that reduced the chance of moisture and aggressive ions infiltrating the interfaces. Commercial finishes, on the

ISSN: 3071-6357
PP: 01-14.

other hand, tended to exhibit localized corrosion and were less likely to stick to their substrate when left in corrosive conditions. The resistance to abrasion of the developed coating was also significantly greater, which expressed its increased mechanical strength and the capacity to sustain functional surface features through several wear cycles. Such point is quite crucial with respect to industrial usage where the surfaces are constantly exposed to mechanical load. In addition, the high foul resistance of the recommended coating decreased the concentration of contaminants and biologic deposits, subsequently lowered the maintenance needs and enhanced the functioning efficiency. The results of the thermo-stability tests indicated that the created coating was Durable to sudden changes in temperature and could resist numerous temperature variations without losing its performance as most commercially available coating did since they developed cracks or delamination. Besides technical performance, the proposed coating also had superior consistency and reproducibility, which indicated the control of fabrication reliability. In general, the comparative study proved that the design of the coating of superhydrophobic demonstrates a combination of durability and functionality in a stable state, which is why it can be offered as an alternative to current commercial solutions to complex industrial service.

5. CONCLUSION

It is a detailed and thorough research on creating, characterizing, and evaluating performance of the superhydrophobic coating by spraying onto an industrial surface. An integrated sol, gel deposition method with surface modification method provided a strategy to obtain a stable, long-lasting nanostructure coating that was successfully obtained and which enables the achievement of a hierarchical micro-nano architecture at the low-surface energy. Optimized fabrication of the process led to good interfacial bonding and entrapment of the nanoparticles between the substrate, the coating matrix, and also between the substrate and coating matrix with uniform surface morphology and increased mechanical integrity. Therefore, the resulting coating was found to have excellent functional properties such as excellent water repellency, better corrosion resistance and better mechanical wear and environmental degradation behavior.

It was experimentally verified that the prepared surface had a maximum contact angle between water in statical position of 162 o which shows a fully developed superhydrophobic state. More to the point, the coating still maintained its hydrophobic properties despite all abrasion, salt spray, and thermal cycling tests, which also demonstrated its ability to remain stable and durable over the long term. Analysis of performance quantitatively demonstrated that it was highly superior to conventional coatings with corrosion resistance being improved by as much as 65% and fouling being mitigated by an average of 58. The synergistic effect of hierarchical surface roughness and chemically bonded low-energy surface modifiers is credited with these improvements and effectively reduced the contacts between liquids and solids and prevented the adhesion of contaminants.

The high levels of durability and versatility of the created coating can imply its high potential in practice of industrial use. Such coatings can significantly increase the service life of industrial equipment and infrastructure by minimizing the level of moisture buildup, corrosion-related

ISSN: 3071-6357
PP: 01-14.

damages and surface contamination. Also, the improved self-cleaning and anti-fouling are added, which leads to the reduced maintenance, lower operation stoppage time, and higher energy efficiency in pipelines, heat exchangers, and marine structures used in renewable energy systems. Economically, these advantages are long term cost savings and reliability of the system.

Although these are positive results, they need to be researched to be applied in large scale. The research in the future should be dedicated towards creation of scalable and cost effective method of manufacturing that is compatible with mass production. Moreover, the employment of surface modifiers that are eco-friendly and toxic-free should gain much importance to reduce the ecological effect. However, long term field tests under actual working conditions in the industry are also necessitated in order to prove the findings in the laboratory and determine the actual performance under actual situation. On the whole, the results of the present research prove that highly complex superhydrophobic surfaces are a promising and efficient way of improving the performance, durability, and sustainability of the industrial surfaces.

REFERENCES

[1] Barthlott, W., & Neinhuis, C. (1997). Purity of the sacred lotus: Escape from contamination in biological surfaces. Planta, 202, 1–8.
[2] Feng, L., Li, S., Li, Y., et al. (2002). Super-hydrophobic surfaces: From natural to artificial. Advanced Materials, 14(24), 1857–1860.
[3] Quéré, D. (2005). Non-sticking drops. Reports on Progress in Physics, 68(11), 2495–2532.
[4] Ma, M., & Hill, R. M. (2006). Superhydrophobic surfaces. Current Opinion in Colloid & Interface Science, 11(4), 193–202.
[5] Nosonovsky, M., & Bhushan, B. (2007). Multiscale effects and capillary interactions in functional biomimetic surfaces. Microsystem Technologies, 13, 1281–1291.
[6] Lau, K. K. S., Bico, J., Teo, K. B. K., et al. (2003). Superhydrophobic carbon nanotube forests. Nano Letters, 3(12), 1701–1705.
[7] Shirtcliffe, N. J., McHale, G., Atherton, S., & Newton, M. I. (2010). An introduction to superhydrophobicity. Advances in Colloid and Interface Science, 161, 124–138.
[8] Wang, S., & Jiang, L. (2007). Definition of superhydrophobic states. Advanced Materials, 19, 3423–3424.
[9] Liu, K., & Jiang, L. (2011). Bio-inspired design of multiscale structures for function integration. Nano Today, 6(2), 155–175.
[10] Zhang, X., Shi, F., Niu, J., Jiang, Y., & Wang, Z. (2008). Superhydrophobic surfaces: From structural control to functional application. Journal of Materials Chemistry, 18, 621–633.
[11] Bhushan, B., & Jung, Y. C. (2011). Natural and biomimetic artificial surfaces for superhydrophobicity. Progress in Materials Science, 56, 1–108.
[12] Verho, T., Bower, C., Andrew, P., et al. (2011). Mechanically durable superhydrophobic surfaces. Advanced Materials, 23(5), 673–678.
[13] Wang, J., Zheng, Y., & Deng, X. (2015). Stability of superhydrophobic surfaces under mechanical abrasion. Langmuir, 31(3), 1134–1141.
[14] Zhang, J., Seeger, S. (2011). Superoleophobic coatings with ultralow sliding angles. Angewandte Chemie International Edition, 50, 6652–6656.
[15] Scardino, A. J., & de Nys, R. (2011). Mini review: Biomimetic models and bioinspired surfaces for fouling control. Biofouling, 27(1), 73–86.