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Recent progress in superhydrophobic coatings used for steel protection: A review☆

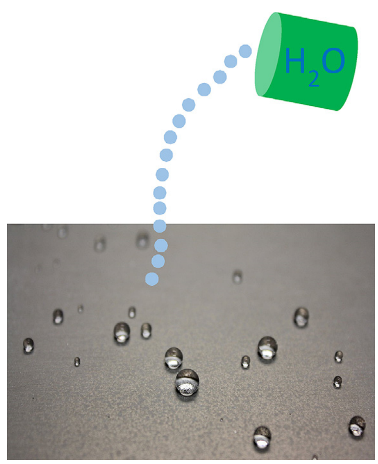
Aziz Fihri*, Enrico Bovero, Abdullah Al-Shahrani, Abdullah Al-Ghamdi, Gasan Alabedi

Oil and Gas Network Integrity Division, Research & Development Center, Saudi Aramco, Dhahran 31311, Saudi Arabia

HIGHLIGHTS

- Different natural models inspiring to the creation of superhydrophobic coatings are introduced.
- The different models used to evaluate the wettability of surfaces are investigated.
- Recent advances in preparation of superhydrophobic coatings are reviewed.
- The challenges related to implementation of superhydrophobic coatings in large-scale industrial applications are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Since the discovery of the self-cleaning properties of the lotus effect, the wetting of surfaces were intensively investigated due to their potential application in many industrial sectors. The corrosion of steel is a major industrial problem and its economic and environmental consequences are widely known. The use of superhydrophobic coatings appear to be one of the promising solutions to protect steel from corrosion effects. This review provides an overview of the superhydrophobic coatings reported in literature for steel protection and their performances. First, to obtain a comprehensive perspective, superhydrophobicity that is present in nature is concisely introduced at the beginning of this review. Second, the different models used to evaluate the wettability of a rough surface and the equations governing the static contact angle are discussed and commented. Finally, the different approaches used to fabricate the artificial superhydrophobic coatings and their impact on the corrosion performance for steel are also examined.

☆ This article is dedicated to the memory of Abdelmawjoud Oirrach, admirable friend and an irreplaceable person.

* Corresponding author.
E-mail address: Aziz.fihri@aramco.com (A. Fihri).

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Contents

1. Introduction

Due to its outstanding mechanical performance and relatively low cost compared to higher alloy materials, steel is widely used in many application domains such as civil engineering, transport, and the oil and gas industry [1]. According to the latest estimates of the World Steel Association published in October 2014, the world steel consumption amounted to 1537 million tonnes in 2014 with an increase of 2% compared to the year 2013 [2]. However, steel has some critical issues owing to its corrosion deterioration especially in marine environments that typically have high salinity and high humidity, two factors that severely affect steel's mechanical properties. An estimated 20% of world steel production is lost each year in the form of rust [3]. There is 1–5% of the gross national product that each nation is spending on corrosion issues [4]. The World Corrosion Organization evaluated an annual cost of around $2.4 trillion expenditure worldwide [5]. While steel corrosion is unavoidable, it can be inhibited by applying organic coatings to maintain the steel's mechanical properties, thereby extending its service life and minimizing maintenance costs. Subsequently, diffusion of water through the anticorrosive polymers coatings is identified as a major contributor to the loss of adhesion, delamination and corrosion under the coating, which consequently leads to frequent coating replacement and significant maintenance costs [6]. The development of superhydrophobic coatings to protect steel from corrosion seems to be a seductive solution. It is difficult for superhydrophobic surface coatings to be wetted, and although the phenomenon of the self-cleaning lotus leaf effect may have been familiar in Asia for at least 2000 years, the study of it is fairly recent. It is only since the early 1970s with the introduction of the electronic microscope that the lotus leaf phenomenon was explored by botanist Wilhelm Barthlott [7]. Since the late 1990s, the development of superhydrophobic surfaces has received tremendous interest due to its potential industrial applications. With the emergence of nanotechnology and the development of manufacturing tools, new processes have been originated. Currently, it is well established that for the development of superhydrophobic surfaces, it is necessary to make surfaces with the coexistence of two properties: A chemical property resulting in a low surface energy of solid and a physical property resulting in the creation of a hierarchical roughness. The purpose of this review is to report the recent advancements in the field of superhydrophobic coatings that were developed to protect steel as well as the different pathways used to enhance their anticorrosion performances. This review will also contribute to a better grasp of the superhydrophobic coating's anticorrosive performance and the limitations that still need to be addressed to be produced for large-scale industrial applications. We have chosen here to focus our efforts on superhydrophobic coatings due to their easier accessibility to almost the entire scientific community, including non-specialists of corrosion and scientists involved with materials science and engineering. The first part of this review will be dedicated to the description of superhydrophobicity in nature, whereas the second section will address the theory of superhydrophobic surfaces. The third main section will strive to provide information on the recent advances related to superhydrophobic coatings used for steel protection and their limitations. Last, the review will provide concluding remarks on this topic.

2. Superhydrophobicity in nature

Nature has always been an inspiration for scientists and researchers and superhydrophobicity is one prime example of such interest. Superhydrophobicity is a physico-chemical phenomenon where a surface is extremely difficult to dampen. This phenomenon is attributed to the coexistence of a chemical property resulting from low surface energy of solid and a physical property translated by creating a hierarchical roughness. On such surfaces, water forms nearly spherical droplets and can be easily shaken away. To control the wetting properties of synthetic materials for targeted applications, it is of major interest today to study and understand the systems already present in nature. Superhydrophobic properties have always been present in nature from time immemorial, as there are many natural materials that exhibit superhydrophobic properties. Barthlott and Neinhuis conducted several studies on natural species and referenced the surface properties of over a hundred vegetable species, including the famed semi-aquatic lotus plant [7]. In their studies, Barthlott and Neinhuis revealed the self-cleaning properties of the surfaces of the lotus leaves. Accordingly, when a water droplet falls on the surface of a lotus leaf it forms spherical beads and can be easily shaken away from the surface while simultaneously removing dust and contaminants that are accumulated on the surfaces of the leaf. Scanning electron microscopy (SEM) analysis of the surface of the lotus leaves revealed that they are not smooth but rather covered by wax nanocrystals. These crystals provide a water repellent layer that is enhanced by the roughness of the surface, thereby making it superhydrophobic [8]. Similarly, many species of animals have superhydrophobic properties on specific or entire parts of their bodies, like the feathers of some species of birds or the wings and legs of some insects [9]. For example, the Gerris spider has been nicknamed "water strider" thanks to its capacity to float on top of the surface of water. It has a special hierarchical structure on its legs that include large amounts of oriented tiny hairs called micro-setae, fine nano-grooves and a covering of secreted cuticle wax. The available air trapped in the spaces between the micro-setae and nano-grooves forms a cushion at the leg-water interface and provides superhydrophobic properties that prevents the spider's legs from getting wet and prevents them to being wetted. If a drop of water could be placed on its leg, it would probably possess the highest contact angle of natural systems: around 167°.