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Influence of corrosion and surface roughness on wettability of ASTM A36 steels

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ABSTRACT

This study aims at investigating the influence of corrosion on water wettability of ASTM A36 steel. To this end, ASTM A36 steel specimens are subjected to different corrosion durations and water wettability of these specimens is determined using contact angle tests based on sessile drop method. Water wettability is found to increase with increase in corrosion of ASTM A36 steels. Pitting corrosion associated with higher corrosion exposure is observed to increase the surface roughness and the subsequent non-uniformity of the corroded surfaces. The increase in the surface roughness due to corrosion is hypothesized as the reason behind the increase of water wettability in corroded specimens. In order to prove this hypothesis, different set of specimens are grinded and polished to achieve a range of surface roughness values. When contact angle tests are conducted on these specimens, it is observed that increase in surface roughness results in increase in the wettability of steel proving the above stated hypothesis. The converse of the hypothesis is also verified by exposing specimens with different surface roughness values to corrosive environment. From a visual examination, specimens with higher roughness values exhibited more corrosion when compared to smoother specimens when exposed to a corrosive environment for same duration. Finally, predictive equations are proposed to estimate the water contact angle of ASTM A36 as a function of surface roughness.

1. Introduction

Corrosion is widely regarded as one of the most common forms of deterioration experienced by steel structures in their service life. Corrosion induced damage poses a significant threat to the safety and integrity of both inland and offshore infrastructure. Maintenance of structures to limit or prevent the damage due to corrosion is a significant issue in United States and other parts of the world [1–3]. In the past, damage due to corrosion has resulted in severe damage and even collapse of both inland and offshore structures causing huge loss of life and property [4–7]. Failure of structures due to corrosion can also adversely affect the environment. For instance, a 2003 offshore hydrocarbon release report attributed approximately 45% of hydrocarbon leaks to corrosion related failures [8,9]. Also, according to Pipeline and Hazardous Materials Safety Administration (PHMSA) statistics, about 17% of pipeline accidents that occurred in the United States in the past 20 years are caused by corrosion induced failures [10]. Corrosion is recognized as one of the primary contributing factors in 20% of all refinery accidents that occurred in European Union countries in the past 30 years [5]. In aviation industry, over 20% of accidents that resulted in a human injury are caused by corrosion failures [11]. The total cost of corrosion related damages in 2016 is estimated to be 2.5 trillion USD globally [12]. The United States [13] and other major economies [11] regularly spend huge amounts of money for repairs and maintenance associated with corrosion damages.

The amount of corrosion induced in structural steel is determined by the presence of oxygen, salt and water in the exposure environment. Corrosion results in loss of material, reduction in section and formation of corrosion products [1]. These factors cause reduction in load carrying capacity of steel members and lead to subsequent failures [14]. Two most frequent corrosion modes with varying implications are observed in steel structures. They are uniform corrosion and localized corrosion [1,15–17]. Uniform corrosion is reported as the most common form of corrosion in steels [15,17]. This type of corrosion occurs uniformly over the entire surface of steel, resulting in thinning of steel section and hence reduction in load carrying capacity of steel members. Localized corrosion occurs locally and does not affect the entire surface area of the steel member [16]. Pitting corrosion, galvanic corrosion, crevice corrosion and stress corrosion among others are some examples of localized corrosion [17]. Pitting corrosion is considered highly critical as it results in stress concentration which in turn serves as crack initiation site reducing the ductility and fatigue life of structural steel members [6,18–21]. Recently, researchers have reported effects of local corrosion on behavior and performance of structural steel using different corrosion models [22–25]. Early detection of corrosion can reduce the associated maintenance costs and improve the service life of steel structures.

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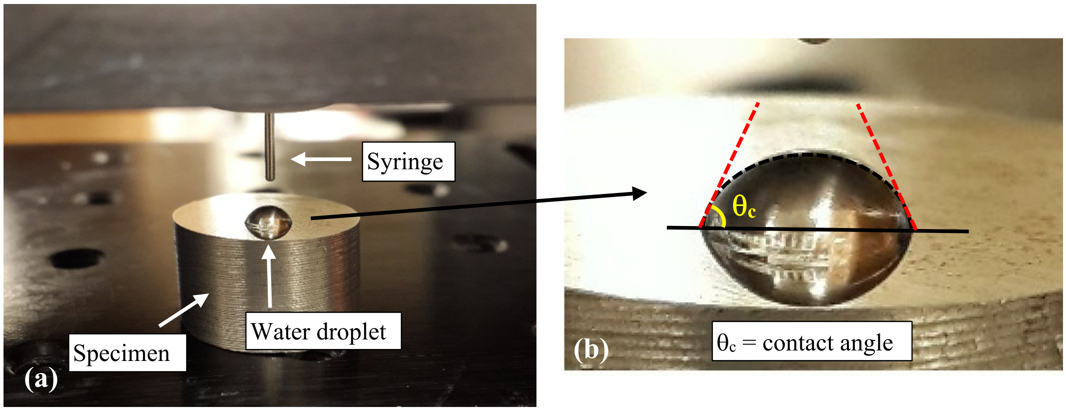

Fig. 1. (a) Typical specimen during contact angle test, (b) contact angle measurement.

To improve the corrosion resistance and service life of structural steels, various coating technologies have been developed [26–33]. In addition to this, weathering steels that do not need coating to prevent damage due to corrosion have been developed using different alloy compositions [34]. However, despite this progress, corrosion remains as one of the significant deterioration processes in many steel structures. Corrosion in structural steel is a surface phenomenon. Therefore, it is imperative to understand the underlying phenomena that affect the amount of corrosion incurred on the surface of steel. The corrosion incurred in structural steels is strongly influenced by water wettability and water wettability of structural steels is not completely understood in the literature.

The interaction between air, water and surface of steel is important in evaluating the wettability and corrosion induced on the surface of steel. Wettability or degree of wetness is the tendency of a liquid to maintain contact with a solid surface [35–37]. Generally, wettability of a surface is influenced by surface chemistry, free energy, surface morphology and properties of the liquid [38–40]. Wettability of a liquid is generally defined in terms of contact angle of the liquid drop [41]. Contact angle (θ_c) is defined as the angle that liquid-vapor interface makes with solid-liquid interface during wetting process, and is illustrated in Fig. 1(b) [37]. Therefore, a high contact angle corresponds to a lower wettability and vice versa. Surfaces that possess a contact angle >90° are referred to as hydrophobic surfaces whereas surfaces with contact angle <90° are referred to as hydrophilic surfaces [42,43]. In other words, hydrophobic surfaces have lower affinity for water whereas hydrophilic surfaces have high affinity for water [44]. It is evident that hydrophobicity or hydrophilicity of a surface will affect the water presence and hence will influence the degree of corrosion on the surface of steel.

Owing to several technological applications, hydrophobic and hydrophilic behavior of surfaces are extensively studied in the past few decades. To improve and optimize the behavior of surfaces, various surface treatments are developed. The objective of such surface treatment mainly involves altering the hydrophobic or hydrophilic nature of the surface to make it more efficient in its intended application. Extensive research in the recent past is conducted to develop superhydrophobic and superhydrophilic surfaces for different applications [40,42,44–55]. More recent research is directed toward developing surfaces with switchable wettability [56–59]. Many of these surfaces with tunable wettability are achieved by mimicking biological phenomena [45,59–61].

Structural steel is intrinsically a hydrophilic material. Surface tension of water is less than the surface energy of a clean steel surface, which results in spreading of water over steel surface [62,63]. However, steel surface is usually categorized as weakly hydrophilic [44] as it develops considerable contact angle in service conditions. This weak hydrophilic behavior of steel surface can be attributed to the formation of oxide layer either in monolayer form or thick oxide form due to its exposure to atmospheric moisture and oxygen [62]. The bonding interactions between these oxide layers and hydrogen of water avoid complete spreading of water on steel surface. Apart from surface chemistry, morphology of surface is another factor that affects the wettability of steel surface. In particular, surface roughness is observed to influence the wettability of steel surface. Surface roughness acts as a porous medium for the liquid, as represented by roughness grooves in Fig. 2. The apparent contact angle of the liquid on such a rough surface is affected by the relative surface energies of both solid and liquid phases. Depending on the interfacial tension between the rough surface and liquid, the liquid drop either follows the grooves and completely fills them up or the liquid drop get pinned to the groove edges due to entrapped air pockets in the grooves caused by surface roughness. The former case, also referred to as Wenzel state [64], is commonly observed in hydrophilic surfaces. The latter case, also referred to as Cassie-Baxter state [65], is typically observed in hydrophobic surfaces. Both Wenzel state and Cassie-Baxter state are illustrated in Fig. 2(a) and Fig. 2(b), respectively. In Wenzel state, the contact line between liquid and solid is completely characterized by liquid/solid surface tension. In Cassie-Baxter state, a composite interface comprising of both liquid/air and liquid/solid interfaces exist at the contact line between solid and liquid due to the entrapped air. The stability of both these states is affected by the geometry and

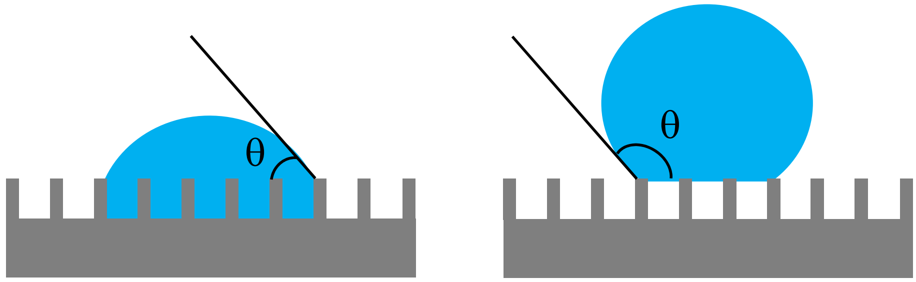

Fig. 2. Illustration of wetting on rough surfaces (a) Wenzel state, (b) Cassie-Baxter state.