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Mechano-electrochemical modelling of corroded steel structures

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ABSTRACT

A numerical methodology is established to study the mechano-electrochemical performance of corroded steel structures under external and internal stresses. Results show that mechanical stimuli (elastic/plastic deformation) increase the local anodic current density, and thus the corrosion behavior dynamically responds to the loading conditions. The current density increment for a multi-component stress system is largely dependent on both hydrostatic pressure and equivalent plastic strain. Moreover, the mechano-electrochemical corrosion is more affected by plastic deformation, resulting in localized areas being more anodic. Existing corrosion introduces extra stress/strain concentration, which further reduces the structural strength capacity and intensifies the corrosion damage.

1. Introduction

In the context of ship and offshore structures, the initiation and progression of marine corrosion may be related to various types of mechanisms, such as galvanic corrosion, intergranular corrosion, crevice corrosion and erosion corrosion [1]. Depending on the age of the structure, corrosion protection system and the environmental factors, the corrosion process can be dominated by one or more mechanisms [2–4]. Particularly, the combined mechanical and corrosion influence is often termed mechano-electrochemical changes in physico-mechanical properties of a solid surface [5]. Previous studies have focused on stress corrosion cracking [6,7], corrosion fatigue [8–10] and hydrogen-induced cracking [11–13] and erosion-corrosion [14–16]. It has been reported that 23–33% of the low-alloy steel weight loss was attributed to the mechano-electrochemical effects, while the number could be 55–62% for austenitic stainless steels [17]. Various experiments and simulations along with theoretical/empirical formulas have been proposed to establish the relationship between stress/strain and the corrosion behavior. However, the conclusions are largely dependent on the metallurgic characteristics of the material and the test environments. In consequence, the synergistic effect of mechanical factors and electrochemical processes remain poorly understood.

An early study carried out by Despic et al. [11] in 1968 reported that during corrosion, only the rate of hydrogen evolution was affected by tensile elastic stress. The chemical potential (the partial molar free Gibbs energy of a substance) of hydrogen was believed to decrease under stress, which lowered the activation energy barrier for hydrogen-metal discharge and hence enhanced the cathodic reaction. Conversely, Gutman concluded that both tensile and compressive elastic stress would equally and directly affect the anodic reaction by increasing the surface chemical potential and reducing the equilibrium potential [5]. Similar conclusions were drawn in Ref. [18]. Generally the influence of elastic stress may vary significantly but is often reported to be limited in magnitude (less than 1 mV [19]). Although care must be taken since the reported measurement provides a total or average value for the entire specimen and may not be representative of the actual conditions which may be present at localized sites [20]. Investigations of plastic deformation effects have been carried out by applying external loading, cold work or welding, which leads to direct and/or residual plastic strain. Under external load, it has been generally agreed that the plastic strain will significantly reduce the corrosion resistance by directly enhancing the anodic reaction [7,11,14,16,21–26] while the hydrogen evolution was reported to increase as well [21,22]. Despic et al. [11] observed that a negative corrosion potential shifted by up to 30 times, with a marked increase in the anodic current density at the onset of the tensile plastic strain and reached an asymptotic value gradually. Plastic deformation was believed to increase the surface reactivity

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Nomenclature

$\bar{\alpha}$	coefficient describing of mobile dislocation density dependence on strain (10^9–10^{11}), cm^{-2}
β	slenderness ratio
$\Delta\gamma$	plastic shearing strain
$\Delta\varepsilon$	macro plastic strain
ν	Poisson's ratio
σ_m	absolute value of the spherical stress in the solid phase, MPa
σ_y	yield stress of the material, MPa
$\Delta\tau$	hardening, MPa
υ	orientation-dependent factor
$\Delta\varphi_{Total}$	total change in the equilibrium potential of a stressed electrode, V
$\Delta\varphi_e$	change in the equilibrium potential of an elastically stressed electrode, V
$\Delta\varphi_p$	change in the equilibrium potential of a plastically stressed electrode, V
a	plate length, mm
b	plate width, mm
b_f	flange width, mm
B	width between two longitudinal girders, mm
E	Young's modulus, GPa
E_t	Tangent modulus, GPa
F	Faraday constant, C mol^{-1}
h_w	web height, mm
i_a	anodic current density of a stressed electrode, A m^{-2}
i_{a0}	anodic current density of a non-stressed electrode, A m^{-2}
k_d	Boltzmann constant for a system of particles representing unit dislocations, J K^{-1} cm
ΔN	increase in the dislocation density at the hardening, cm^{-2}
N_0	dislocation density when no hardening, cm^{-2}
N_{max}	maximum possible dislocation density, cm^{-2}
n	number of dislocation in planar pile-ups
R	gas constant, J mol^{-1} K^{-1}
t	original plate thickness, mm
t_f	flange thickness, mm
t_{gc}	remaining thickness due to grooving corrosion, mm
t_p	thickness reduction due to pitting corrosion, mm
t_w	web thickness, mm
T	absolute temperature, K
V_m	molar volume, m^3 mol^{-1}
w_c	column-type initial deflection, mm
w_{gc}	width of grooving corrosion, mm
w_{pl}	plate initial deflection, mm
w_s	sideways initial deflection, mm
z	number of electrons within the partial electrochemical reaction

non-uniformly [26] and the stored energy within a material, which can be directly related to the electrode potential change [27]. The increased current density at an early stage of cold rolling and a decreased value in the dynamic recovery stage of the hardening process corroborated the observations under external loading [28]. In terms of welds, electrochemically more negative potentials have been detected in the vicinity of weld boundary using either a micro-capillary probe or Kelvin probe [5,29,30]. The relatively high potential on the weld bead was reported to be induced by a thick oxide film [30] as well as a lower residual stress in comparison to the base metal [5]. More recently, due to the increase in the computational capability, research of mechano-electrochemistry has been achieved numerically with implementation of Gutman's formulas [5] to provide more detailed information on the corrosion enhancement [31,32].

Regarding corrosion on marine structures (ships and offshore platforms/pipelines), large-scale pitting and grooving corrosion are considered to be major forms of localized damage [33], which has a more significant impact on the structural resilience compared to uniform/general corrosion [34,35]. Pitting is frequently associated with coating breakdown or ineffective cathodic protection, which leads to pits that are tens of millimeters in diameter. Fig. 1 shows a 3D surface profilometry of typical pitting damage on the inner bottom plating of a 15–16 years old bulk carrier, where broad pits with vertical walls can be easily observed (Fig. 1(b)). At the weld joints of large steel panels, grooving corrosion (also referred to as preferential weld line, knife-line or trench-like corrosion) may occur, which is a selective and rapid corrosion along a weld joint [33,36]. The mechanisms of grooving corrosion is considered to be a much more complex situation. Indeed it has been previously reported that galvanic effects arise from differences within the metallographic structures (welds, heat affected zone (HAZ) and the base metal) and/or the inclusion of MnS stringers [36]. Also, weld imperfections (spatter) subsequently mean a thickness fluctuation of an applied protective coating, and hence exacerbate the corrosion. For both corrosion types, experiments have showed that the deformation/flexure of structures in service would inevitably result in protective layer (coating and/or rust) flake-off and hence an accelerated damage in the long term [37]. And last but not least, the in-service stresses and the above mentioned weld-induced residual stresses may have a significant influence on the surface chemical state [5]. General practices in assessing the corrosion condition in aged marine structures can be found in Ref. [38].

A marine structural system will endure various loading throughout its lifetime. Within the system, which is often consisting of a number of different structural members, some members will always reach their collapse or ultimate strength first before the whole system collapses. Thus, taking into account the ultimate strength and post-collapse behavior of individual structural members is essential to determine the overall integrity of a structural system. There has been significant effort to assess the strength capacity of steel marine structures with uniform corrosion [39,40] and localized corrosion damage using both experimental and finite element (FE) methods [34,41], varying structural geometries, corrosion extent, loading/boundary conditions and structural initial imperfections. While the influence of pitting corrosion has been investigated in depth over the last decade [42–46], grooving corrosion has gained increasing attention only recently [47–49]. Considering that both corrosion types will result in stress/strain concentrations, however, only a limited number of studies have addressed the mechanically assisted reactions on the corrosion performance of marine structures loaded to an ultimate condition. In addition, the frequently used Gutman method needs to be appropriately considered for structures in a multi-component stress state. This paper studies the mechanical and mechano-electrochemical performance of steel structures subjected to localized corrosion damage (assuming charge transfer control and neglecting the presence of protective coatings or oxide layers), using previously constructed pitting and grooving FE models [45,48] in order to predict corrosion acceleration at 'hot spot' locations induced by stress/strain effects and to quantify the corrosion enhancement.