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Effect of corrosion and hydrogen embrittlement on microstructure and mechanical properties of mild steel

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HIGHLIGHTS

- Investigation and quantification of the degradation effect of corrosion on mechanical properties of mild steel.
- Hydrogen embrittlement attributes to the degradation of mechanical properties.
- Changes in element composition and microstructure also cause the degradation.
- Immersion test provides better estimation of hydrogen damage than charging test.
- Intergranular corrosion occurs for mild steel during corrosion.

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ABSTRACT

This paper investigates the effect of corrosion on degradation of mechanical properties of G250 mild steel. Corrosion tests are conducted by immersing steel into hydrochloride acid solutions, with acidity ranging from 0.00001 M to 3 M. Both macro analysis and micro analysis are undertaken to investigate the mechanism of corrosion induced degradation of mechanical properties. Intergranular corrosion is found for mild steel during corrosion. Results indicate that there is considerable reduction in mechanical properties due to corrosion, which is attributed to a combined effect of hydrogen embrittlement, changes in element composition, grain size and phase composition, and the residual stress concentration at corrosion pits.

1. Introduction

Mild steel, steel with carbon content from 0.15 to 0.20%, is widely used in construction of bridges, buildings, and pipelines [1]. Steel corrosion is the biggest environmental threat faced by steel structures. Corrosion can lead to losses of cross sections and reduction in yield strength, ultimate strength, and ductility. It reduces service life of structures and makes the structures vulnerable to structural failure [2]. Therefore, it is vital to monitor and quantify the corrosion behavior and corrosion impact of mild steel structures, in order to optimize maintenance, repair, and rehabilitation.

The prediction of corrosion effect on structural integrity of structures and infrastructures, in most of the cases, has been investigated by considering section loss [2]. However, some recently published literature suggests corrosion also has degrading effect on mechanical properties (i.e., yield strength, ultimate strength, and ductility). Revie [3], Marcus [4], and Eggum [5] stated that corrosion reduces the yield strength, ultimate strength, and ductility due to hydrogen accumulation within steel, which is known as hydrogen embrittlement. In details, corrosion process is a combination of oxygen reduction reaction and hydrogen evolution reaction (Eqs. (1)–(4)). Atomic hydrogen is released during these reactions. It then accumulates at voids or defects within steel forming molecular hydrogen. The molecular hydrogen leads to inner pressure increment and micro crack initiations, which consequently degrades mechanical properties of steel.

Oxygen Reduction Reaction (ORR):

$$\frac{1}{2}O_2 + 2H_3O^+ + 2e \rightarrow 3H_2O \text{ Acid} \quad (1)$$

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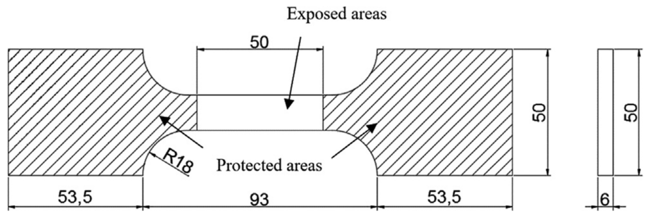

Fig. 1. Specimen for tensile test (Unit: mm).

$$\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2OH^- \text{ Neutral alkaline} \quad (2)$$

Hydrogen Evolution Reaction (HER):

$$H_3O^+ + e \rightarrow \frac{1}{2}H_2 + H_2O \text{ Acid} \quad (3)$$

$$H_2O + e \rightarrow \frac{1}{2}H_2 + OH^- \text{ Neutral, alkaline} \quad (4)$$

Literature suggests that element composition of steel affects its mechanical properties [3,4]. Corrosion may increase the oxygen composition due to the formation of brittle rust layers [6,7]. Simultaneously, iron composition may be reduced during corrosion reaction. Exposing steel to chloride enriched environment also results in chloride penetrations [8], in which chloride ion breaks the passive layer formed during corrosion and makes the steel vulnerable to pitting corrosion and stress corrosion cracking [9]. It is reasonable to believe corrosion changes element compositions of steel and consequently leads to the degradation of mechanical properties. However, there is a lack of research on monitoring the changes in element composition during corrosion.

Corrosion may also lead to degradation of mechanical properties by changing three microstructural features: (1) grain size, (2) phase composition, and (3) formation of corrosion pits [10–13]. Zhou and an Yan [12] pointed out that corrosion reduces the grain size through intergranular corrosion. The bonding force among grains can be weakened during intergranular corrosion, which degrades the mechanical properties of steel. Shanmugam et al. [14] and Olasolo et al. [15] indicated that steel contains two main phases judging from its crystal structure, namely ferrite and pearlite. Ferrite is known as α-iron (α-Fe) which provides steel with ductility and yield strength, and pearlite is composed of ferrite (α-Fe) and cementite (Fe_3C) that makes steel brittle [11]. Sun et al. [13] revealed ferrite is corrosion prone and cementite is corrosion resistant. Furthermore, Revie [3] and Turnbull [16] stated that the mechanical properties are declined due to the existence of pitting corrosion, as stress concentration happens at corrosion pits.

There are several limitations in existing researches. To begin with, hydrogen embrittlement phenomenon has been mainly carried out for high-strength low-alloy steel (HSLA) and stainless steel [3,16–20]. For example, Zucchi et al. [17] found hydrogen embrittlement can lead to degradation of mechanical properties of stainless steel by charging hydrogen into steel sample. Hardie et al. [18] found there is a drop in mechanical properties after high-strength low-alloy steel (HSLA) is charged with hydrogen. For low carbon structural steel, namely mild steel, Chalaftris [20] indicated that

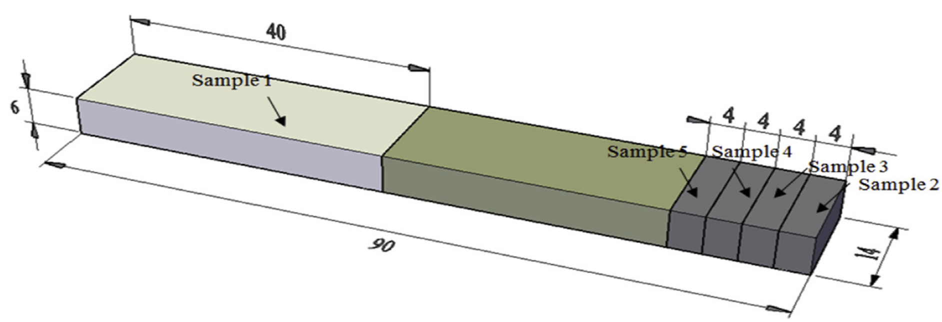

Fig. 2. Specimen for hydrogen concentration, element composition and microstructure test (Unit: mm).

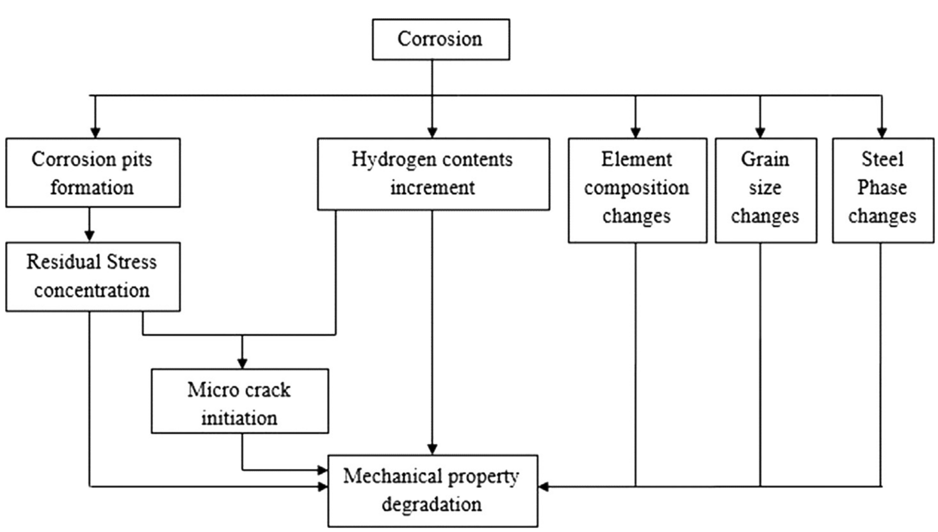

Fig. 3. Process of mechanical properties degradation due to corrosion.