Stress Corrosion Cracking of a Mild Steel in Orange Juice

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***Abstract* — Stress corrosion cracking (SCC) results from the combined action of three factors: the tensile stresses in the material, a corrosive medium and elevated temperature. In this study, the stress corrosion cracking and microstructural analysis of a mild steel immersed in orange juice medium was investigated using weight loss technique and SEM analysis. The mild steel coupons were heat treated to various austenitic temperatures, cooled in water and immersed in orange juice. The weight losses of the mild steel samples were measured at a two days interval and the corrosion rate was the determined. The results obtained show that SCC relative to mild steel is mainly a function of the acidity of the medium under study, and the corrosion rate increases with increase in exposure time throughout the exposure time. Also, the higher the austenitic temperature the more the resistance to corrosion attack due to higher hardness obtained at higher temperatures. The SEM analysis revealed that the transgranular and intergranular attacks were visibly responsible for the corrosion of this material in this medium. The evolution of hydrogen at low pH of the medium due to the presence of acidic citric acid eliminated the possibility of protective formation on the throughout the exposure period.**

***Abstract*— Stress corrosion cracking, mild steel, orange juice**

I. Introduction

Corrosion is a naturally occurring phenomenon commonly defined as the deterioration of a material of construction or its properties due to a reaction with the environment [1]. Corrosion can cause dangerous and expensive damage to manufacturing plants. The corrosion of metals involves a whole range of factors which may be chemical, electrochemical, biological, metallurgical, or mechanical – acting singly or conjointly [2].

Corrosion can take many forms; the form that is under this study is the interaction of corrosion and mechanical stress to produce a failure by cracking. This type of failure is known as stress corrosion cracking (SCC). SCC is cracking due to a process involving conjoint corrosion and straining of a metal due to residual or applied stresses. It is one type of environmentally induced cracking, which can be characterized as corrosion-assisted brittle cracking under low stress [3,4].

The mechanism of stress corrosion cracking is not well understood. This is mainly due to the specific features of SCC being the result of a complex interplay of metal, interface and environment properties. As a result of this different combinations of solution and stress are seldom comparable and the most reliable information is obtained from empirical experiments. The three conditions necessary for SCC to occur are a critical service environment, a susceptible alloy, and a constant tensile stress above some threshold stress [3].

Corrosion has been a major problem in food processing industries, where in the loss of production time for maintenance and equipment failure, there exists the additional risk of product contamination by corrosion products which may results in food poisoning. Corrosive effects are of remarkable consequence in the food processing industry as fruits contain corrosion aggressive substances, thereby causing significant impact on the degradation of constructional materials and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions. The important material used in the manufacturing sector is mild steel. It is usually selected because of its strength, ductility and weldability [5,6]. Mild steel corrodes when exposed to air and the oxide formed on it is readily broken down, and in the presence of moisture, if it is not repaired [1,7]. Table I shows the alloy-environment systems that are prone to SCC.

TABLE I
ALLOY-ENVIRONMENT SYSTEM THAT ARE PRONE TO SCC

Alloys	**Environment**
Carbon steel	Hot nitrate, hydroxide, and carbonate/ bicarbonate solutions.
High strength steels	Aqueous electrolytes, particularly when containing H_2S.
Austenitic stainless steels	Hot, concentrated chloride solutions, chloride containing steam.
High Ni alloys	High purity steam
Aluminium alloys	Aqueous chloride, bromide and iodide solutions.
Titanium alloys	Aqueous chloride, bromide and iodide solutions, organic liquids, N_20_4
Magnesium alloys	Aqueous chloride solutions.
Zirconium alloys	Aqueous chloride solutions, organic liquids.

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The organic acids present in most foods are the most important corrosion agents. The effects of these chemicals can be influenced by the environmental conditions of processing such as temperature, flow rate, viscosity of the food media, and presence of stresses in the system [8]. Organic acid contains citric acid hence known as citrus fruit, citric is a mild acid with a pH of 3.5 of which when exposed to mild steel can form stress corrosion cracking on the steel. The exact analysis of the constituents of food stuff is a challenge due to their very complex compositions. Citrus species are utilized in many industries for the production of various brands of citrus juices [9].

Therefore, a reaction between steel (Fe), moisture (H_2O) and oxygen (O_2), takes place to form rust [13]. This reaction is complex but it can be represented by a chemical equation (i):

$$4FE + 2H_2O + 3O_2 \rightarrow 2Fe_2O_3\ .H_2O \qquad \text{(i)}$$

Sanusi and Hussein in 2010 [10] identified that mild steel corrosiveness relatively makes it undesirable economically and health-wise because these corrosion products may find their ways into the bulk of the juice causing off-taste, off-flavour and off-texture which may equally be hazardous to health.

This study examines the SCC and microstructural analysis of mild steel in orange juice environment in other to provide a better understanding of the corrosion behaviour of the this material in this medium, thereby enhancing the material selection and effective surface treatments to increase corrosion resistance, and to ensure environmental worker safety and product quality often created from equipment failure. Considerable research will be carried out in order to understand the effect of these specific factors which occurs on susceptible material as a result of the synergistic effects of tensile stress and corrosive environments and major life threatening issue for food manufacturing industries equipments such as in the production of orange juice. The knowledge of SCC in food industries detect the unfavourable alteration in a system/equipment, and these alterations are acknowledged as damage which could lead to carry terminal point of the structure's life or decreased efficiency.

II. MATERIALS AND METHODS

Mild steel sample of 2 mm thickness, 60 mm length by 60 mm width was used in this study. Its chemical compositions as supplied by the manufacturer are shown in Table II. These steel samples were surface-prepared using emeryl cloth, ethanol and water and were marked. The mild steel sample was then heat treated to austenitic temperatures at 800°C, 850°C and 900°C and soaked at these temperatures for 1 hour before were quenched in cold water to induce stress. Each of the weighed heat treated steel samples were then immersed in an orange juice with a measured pH of 3.27 for 30 days. The weight losses of the samples were measured at every 2 days intervals using the procedures procedures and precautions described by Chen *et al*, [11], Ashassi-Sorkhabi *et al*, [12] and Jabeera *et al*, [13].

The average corrosion rates of the mild steel coupons were determined using:

$$MPY = 534\frac{W}{AT\rho} \qquad \text{(ii)}$$

MPY = mils per year
W = weight loss, mg
A = area of specimen, in²
T = exposure time, hr
ρ = density of specimen, g/cm³ (7.85 g/cm³)

TABLE II
CHEMICAL COMPOSITION OF THE MILD STEEL SAMPLE

Element	C	Mn	P	S	Si	Fe
Weight %	0.25	1.60	0.04	0.0035	0.5	Bal

III. RESULTS AND DISCUSSION

The stress corrosion cracking and microstructural analyses of a mild steel sample immersed in orange juice medium were investigated in this study. Mild steel is an important material that is generally used for various technological applications. This category of steel like most metals and alloys, react with air even at ambient temperature. Heat treatment is carried out on metals to modify their microstructures in other to effect changes such as chemical and mechanical properties based on the proportion of retained austenite, relative grain size and the presence of lattice defects such as dislocations, twinning and vacancies [14,15]. In other words, the main purpose of heat treatment is to produce the desired properties by controlled application of heat and rate of heating and cooling. In this study the mild steel samples were subjected to quenching form of heat treatment to induce stress within the matrix of the steel thus renders it susceptible to stress cracking under the influence of corrosive medium. This heat treatment process is expected to change in the microstructure and corrosion response of this alloy depending on the retained microstructure after the heat-treatment process.

Fig. 1 shows the results of the variation of the weight loss (gm) as a function of exposure time (days) for the samples at 800°C, 850°C, 900°C austenitic temperatures when they were immersed in an orange juice medium. The results presented herein are the average values of three measurements which were taken at room temperature. From the Figure, it can be observed that the weight losses of all the samples increased with exposure time, which means that the corrosion rate also increased with increase in immersion time. This can be attributed to the fact that the corrosion products on these samples were not protective thus allowed continuous attack by the medium. It can also be observed that the sample heat treated at the 800°C austenitic temperature shows the highest loss of weight with time followed by the sample austenized at 850°C, and the sample heat treated at 900°C responded least to weight loss in this medium when compared to the control sample which is more susceptible to corrosion at the same medium. This behaviour indicates that the higher the austenitic temperature the lower the corrosion attack of orange juice on this material. Quenching of these samples in water created hardening which resulted to brittleness of these samples. At higher austenitic temperature the hardness is expected to be more which means that the sample will become more brittle. It can be inferred that at high austenitic temperature such as 900°C, the sample was too high for easily reaction with the medium under investigation. This led to reduction in the corrosion attack of these samples as the austenitic temperature increased.

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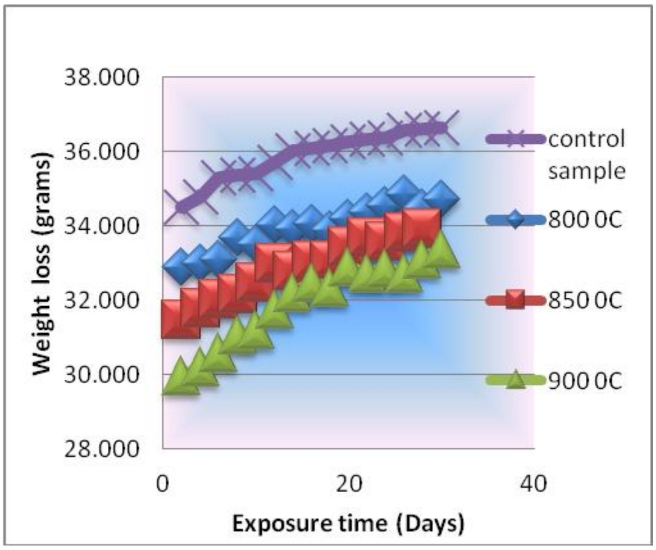

Fig. 1. Weigth loss versus exposure time for the mild steel samples

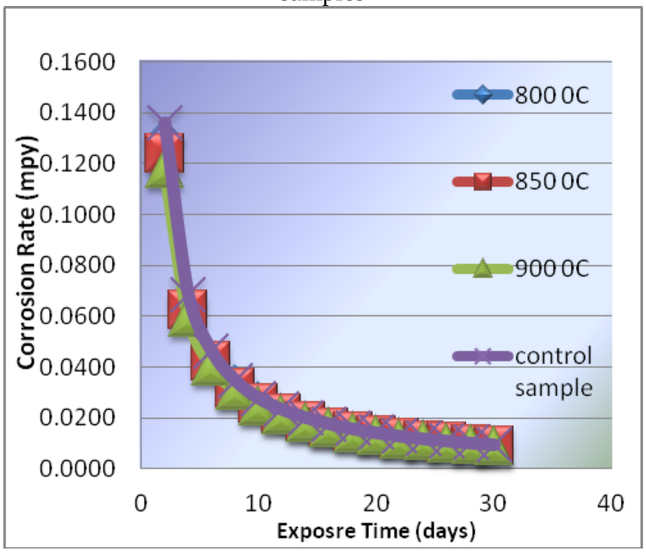

Fig. 2. Corrosion rate versus exposure time for the mild steel samples

Fig. 2 shows the results of the variation of the corrosion rate (mpy) as a function of exposure time (days) for the samples austenized at 800^{o}C, 850^{o}C, 900^{o}C and immersed in an orange juice medium. From this Fig. it can be observed that the samples have similar behaviour as the weight loss results in this medium even at different heat treatment temperatures which also confirms that the corrosion behaviour of these samples increased with exposure time.

Fig. 3 shows the scanning electron microscopic (SEM) analysis of the as-received mild steel sample, the samples heat treated at 800, 850 and 900^{o}C austenitic temperatures. The comparison of these samples indicates that line cracks can be observed at the grain boundaries of the heat treated samples whereas such cracks are not noticeable in the control sample. The behaviour is attributed to the quenching process these heat treat samples were subjected to. Quenching is a hardening process which is usually associated with brittleness in steels and depends on the carbon contents of the steel material. Thus the higher the carbon contents in the steel the more the brittleness in the hardened steels. This behaviour can also be attributed to the residual stresses in these metals which were brought about by the hardening effect of quenching process carried out on them. It can also be observed that the residual stresses developed in these samples increase with the increase in austenitic temperature. For instance, the cracks present in sample heat treated at 850^{o}C are more than those in samples heat treated in 800^{o}C.

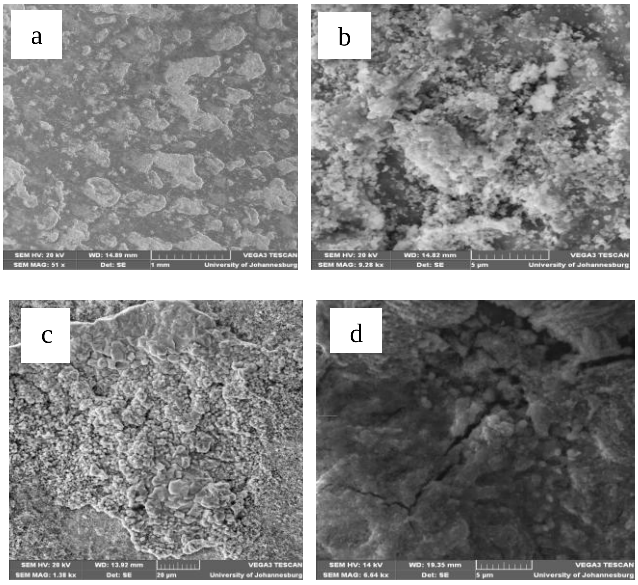

Fig. 3. SEM images of (a) control, samples heat treated at (b) 800 (c) 850 and (d) 900^{o}C before exposure to corrosion medium

The SEM images of the control and heat treated samples after exposure to the corrosion medium are presented in Fig. 4. From these images it can be observed that the SEM analysis shows that a form of either transgranular or intergranular attack is observable on the heat treat samples. The mechanism of this attack can be attributed the oxidizing nature of the orange juice due to the presence of substantial content (80 – 90%) of citric acid in this agro fluid [16-18].

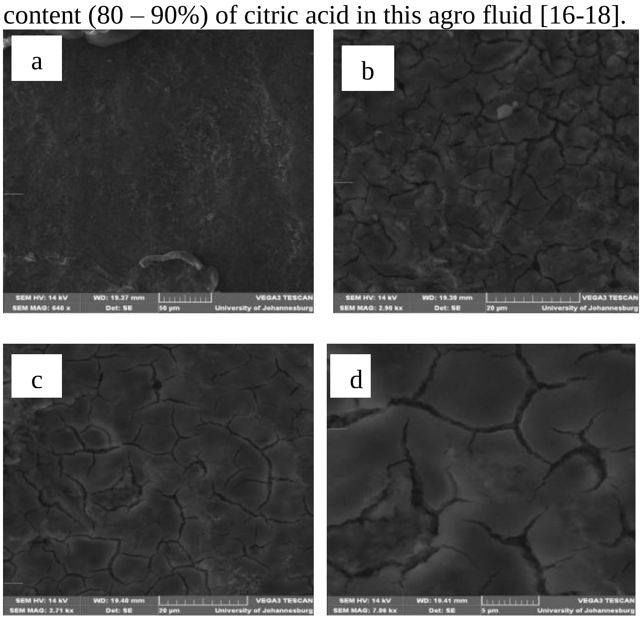

Fig. 4. SEM images of (a) control and samples heat treated at (b) 800 (c) 850 and (d) 900^{o}C immersed in orange juice

The cracks in these samples acted as small anodic sites where corrosion was initiated and propagated as the exposure time increased. This form of attack is very dangerous since there is large ration of cathode to anode site which enables fast propagation of this attack. The acidic

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nature of the medium also could have facilitated the evolution of hydrogen gas which is sometimes terms hydrogen cracking.

IV. CONCLUSION

The SCC and microstructural analyses of mild steel samples immersed in orange juice medium was investigated using weight loss technique and SEM analysis. The mild steel samples were heat treated to various austenitic temperatures, quenched in water and immersed in orange juice with known weight for 30 days. The results obtained showed that SCC occurred in these materials in form of transgranular and intergranular. The corrosion rate of this metal in the medium under study increased with increase in exposure days while the austenitic temperature had a marked effect on the corrosion rate of mild steel samples. The corrosion behaviour of mild steel in this medium is traceable to the evolution of hydrogen gas (due to cathodic reaction) which occurred at low pH and eliminated the possibility of protective layer on this metal in the medium.

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