Corrosion of Prestrained Reinforcement Steel

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Abstract. Steel alloys are widely used in outdoor applications where corrosive media exist and contribute to a great loss in components dimensions and strength. Reinforcement steel bars suffer from corrosion as other steels do. This work is intended to study any possible effect to prestraining of this material on the corrosion behavior. Uniform prestraining was caused on specimens made of two types of reinforcement steel bars. Two degrees of prestraining were included and two corrosive media were implemented in the study. The weight loss method for determining corrosion rates was used. Stress relieving of specimens was also considered and results of corrosion rates at different conditions were compared and discussed. Results indicated that prestraining slightly increased the uniform corrosion rate of tested materials, while this effect diminished with stress relieving specimens before immersion.

Keywords: Corrosion rates, weight loss, saline solution, prestrain, reinforcement, steel alloy, stress relief.

1. Introduction

Corrosion is one of the most effective mechanisms of metals degradation and failure. The total damage of materials due to corrosion costs the UK around 4% of GNP per annum[1]. Corrosion costs U.S. industry and government agencies an estimated $276 billion/year, according to the study by CC Technologies for the Federal Highway Administration (FHWA) published in September 2001[2]. A tremendous amount of literature about corrosion and factors affecting its behavior exists. Corrosion (chemical corrosion) occurs for metals and alloys

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either in dry or in wet conditions. Corrosion starts at heterogeneities on the metals' surfaces. Theses heterogeneities can be on different scales[3]:
- Atomic (point defects, vacancies, and kinks sites)
- Microscopic (grain boundaries and between phases)
- Macroscopic (grain boundaries and discontinuities)

While the rusting developed on the iron and steels is considered the first stage of corrosion, the extent of corrosion depends upon many factors. The most important of these factors are:
- Material compositions (alloying elements, phase constituents, *etc.*)
- Surface condition (roughness, treatment, *etc*.)
- Corrosive media and local conditions

Iron and its alloys constitute most of the research on corrosion since they come on top of most materials used in different applications. Carbon content, as a primary alloying element for steels, was found to be of slight or no effect on corrosion rates by Lopez *et al.*[4] especially at lower temperatures. Also, Melchers[5] stated that carbon content and microstructure are not independent factors in determining corrosion rate. He concluded that more work yet has to be done to investigate that issue. In his recent paper[6], he indicated that metal composition is more effective in corrosion at the first phase of corrosion (kinetically controlled) but not effective during oxygen diffusion controlled phase. Abdel-Aal *et al.*[7] attributed combined effect on corrosion to carbon content according to corrosive medium like acetic, oxalic and cetric acid. Nickel content in low steel alloys[8] was found to work on overall reduction of corrosion rates by decreasing the lattice diffusion of hydrogen. Nishikata *et al.*[9] concluded that nickel content less than 5% suffers of increased corrosion rates, while above that percentage of corrosion rates, corrosion due to cyclic wet-dry environments greatly decreases. Surface finish was found to affect the corrosion conditions effectively[3, 10-12]. As a general conclusion, the better the surface condition the better corrosion resistance of that surface. Aqueous pH increases to some extent corrosion rates[13-15] then decreases with further increase of pH values. For immersed components, flow versus static condition was having some impact on corrosion but not patterned as well as salinity[16, 17]. They had different trends along versatile range of materials.

As a result of hydrogen or water existence around ferrous components, the anodic reaction in which the iron atoms can free two electrons ($Fe \rightarrow Fe^{++} + 2e^-$) to be used in cathodic reaction ($2H^+ + 2e^- \rightarrow H_2$) takes place. In the presence of oxygen (O_2), the cathodic reaction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) occurs so that ferrous hydroxides form ($Fe^{++} + 4OH^- \rightarrow Fe(OH)_2$). The ferrous hydroxide in turn is oxidized to ferric hydroxide $Fe(OH)_3$. The final product is

the familiar reddish brown rust $Fe_2O_3.H_2O$. In a restricted supply of oxygen, Fe_3O_4 or Fe_2O_3 is formed instead. These products depend mainly on the oxygen content and the surface roughness of the component. A model for the uniform deposits, *c*, was presented[18]:

$$c(t) = At^B \qquad (1)$$

Where *A* and *B* are constants determined from experimental data. Stress corrosion, SC, and stress corrosion cracking, SCC, on the other hand are the case where corrosion takes place in existence of component being under stress, which is the actual service condition of most components in real life. Stress corrosion is considered one of the most important topics attracting majority of investigators. The rusty film which develops uniformly on the surfaces, its increased depth was found to increase the resistance to SCC. That was concluded[19] for investigated U-bend specimens of 304 stainless steel in high temperatures. Other factors affecting SCC were studied by many researchers[20-23] such as acidity and alkalinity of the working environments, service temperatures, nature of applied stresses, and composition of working alloys.

Among the variety of applications of components, which are subject to corrosion, is reinforcing of concrete by steel. Also, commercial steels used for this purpose may be subject to prestraining due to forming in different shapes. This may raise the question of the possibility of the effect of this prestraining on the corrosion behavior of such components. Mills and others investigated this aspect partially in their research project[23]. They did not discuss the effect of prestraining directly on the corrosion behavior, but they used prestraining to create residual stresses to different levels and investigate its reflection on the components corrosion rates. The main purpose of this work is to investigate the possible effect of prestraining itself (as a source of massive generation of dislocation density), since cold working and many other manufacturing processing leaves components with a considerable prestrain amount. Investigating such components corrosion behavior was meant by this work. A variation of corrosive media, by taking two different saline solutions into considerations, was taken into account. Two commercially steels used for reinforcing concrete were used to conduct the experimental work. Also, two degrees of prestraining were implemented, so three specimens were used from each material for the purpose of making the needed comparison to show the effects of chosen parameters. Hypothetically, if specimens were put into tensile test and unloaded after plastic deformation was reached as shown in Fig. 1, a certain amount of dislocation density is developed. This dislocation density will increase with the increase of the amount of plastic deformation of the specimen (points 1 and 2 in Fig. 1). Corrosion behavior of such specimen when subjected to a corrosive medium can answer the question. Accordingly, two degrees of prestraining were used

for this work. The degree of prestraining was determined after making a complete tensile test and selecting two points on the stress-strain curve (Fig. 2). Two materials were selected for this work (they are commercially used for reinforcing concrete) and specimens were machined to the standard ASTM dimensions. Two groups of the two materials were used, one group was used as received and the other group was stress relieved then used.
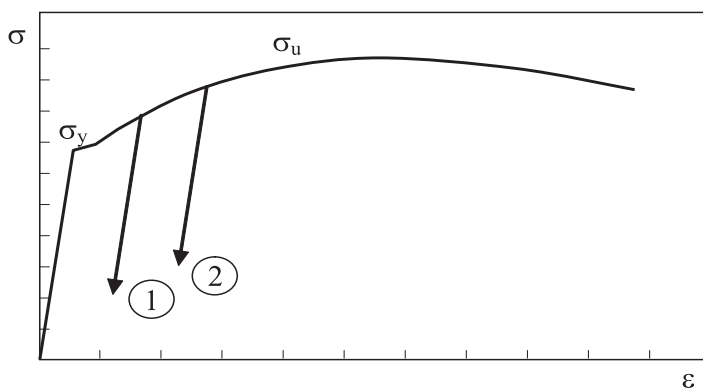

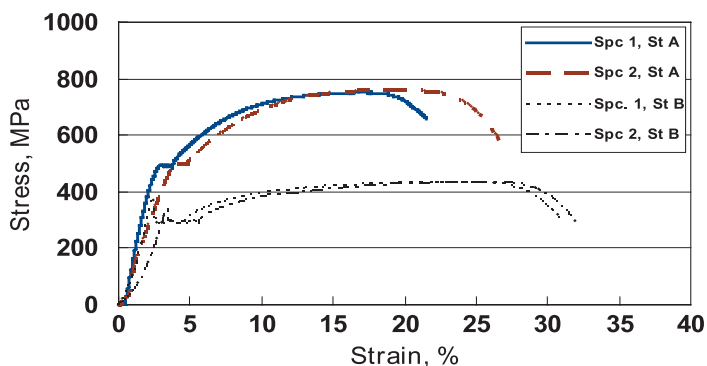**Fig. 1. Schematic drawing showing prestraining of used specimens.**

Fig. 2. Tensile response of the two used steels, designated A and B.

2. Materials and Experimental Work

Two steel materials commercially used for reinforcement of concrete were the target of this study. Elemental analyses were performed for both materials, designated as steel A and steel B. These analyses are presented in Table 1. The elemental analysis shows that steel A contains higher carbon content compared with steel B. This is clear by the microstructure photos for both materials as shown in Fig. 3. Material A constitutes mostly of ferrite with some pearlite

while pearlite constitutes the major phase in material B. This is clearly reflected on the mechanical response of both metals (Fig. 2). Standard tensile specimens with circular cross sections were prepared from both materials and tensile tests were performed using universal tensile testing machine (A 200 KN loading capacity)[†]. Results of standard tensile tests are presented in Fig. 2. Based on the results of tensile tests, prestraining points were defined (at approximately 6%, 12%) and used to generate the prestrained specimens as shown in Fig. 1. More than one degree of prestraining were performed to generate variety of specimens to help investigate any relevant effect on corrosion rates for these materials.

Table 1. Composition of the investigated materials.

Constituent	C	Si	Mn	P	S	Cr	Mo	Ni	Cu
Material A	0.372	0.11	0.7	0.01	0.04	–	–	0.02	0.03
Material B	0.13	0.126	0.496	0.611	0.012	0.09	0.01	0.136	0.199
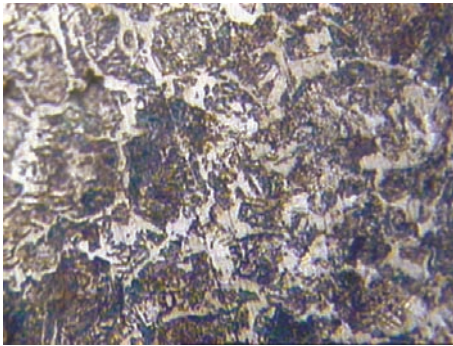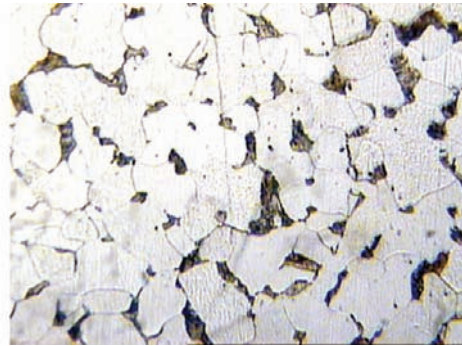
Material A, at 500 ×   Material B, at 500 ×

Fig. 3. Microstructure of the two used steels, designated A and B.

2.1 Preparation of Specimens

The middle part of each prestrained specimen was cut and used for corrosion tests. A total of about 40 specimens were prepared to be used for corrosion tests. Two kinds of specimens groups of each material were prepared. A group of specimens without any treatment (as received) were prepared. Another group of specimens were prepared after being stress relieved. The same procedure was followed on the specimens for both materials designated as steel A and steel B. Specimens made from stress relieved bars were prestrained after stress relieving was performed.

[†]Testometric 200 KN. VITFK International Ltd., Manchester, England.

Corrosion tests were conducted under two kinds of saline solutions. It was meant to simulate the concentrations of Red and Mediterranean Seas (40,000 mg/L NaCl and 35,000 mg/L NaCl respectively). Same amount of the aqueous solutions were used for each specimen. Determination of weight loss of the specimens in a corrosion experiment is one of the common methods to calculate corrosion rates[24]. The coupons were degreased in trichloroethylene, and oxides were removed mechanically with fine emery paper. Each coupon was washed under running water, dried with alcohol and ether and weighed accurately before and after the experiments to remove the surface and/or corrosion products. This method can, in principle, be used in all laboratory methodologies, and for monitoring corrosion rates in the field using coupons. Experiments were carried out over a temperature range from 25 to 28ºC. Each time weight was taken, specimens were carefully washed and solution was changed (using the same amount and concentration). Each specimen was placed in a different container by itself. A sensitive scale (with four digits) was used to measure the weight of specimens. Weight loss was calculated using the equation:

$$\Delta W = W_0 - W_i \tag{2}$$

Where W_0 is the original weight of specimens before immersion in solution and W_i is the specimen weight after immersion for time i. Corrosion rate was calculated based on the equation:

$$\dot{W} = \frac{\Delta W}{A \ \Delta t} \tag{3}$$

Where A is the surface area of the specimen and Δt is time elapsed for immersion for ΔW to corrode. The term $\dot{W}$ can be expressed in mass units per time units or penetration depth (mm/time) if it was divided per density (ρ) as needed.

3. Results

The results of collected data were analyzed and transformed into corrosion rates based on equation (3). Groups of data were plotted in Figs. 4-7. In all figures, "PreStrn" was used to designate specimens that were prestrained, and "No PreStrn" for specimens without prestraining. Also, "Env I" and "Env II" were used to designate solutions of immersions I and II. Figure 4 contains corrosion rates of specimens made of steel A as received (No treatments were made). Periods of collecting data (Weight) were uniform (weekly) except for third and sixth readings. Corrosion rates (for both materials) were slightly increasing with immersion time except at readings number 3 and 6. Data points of corrosion rates in solution I (35,000 mg/L) were plotted in solid lines with filled marks, while data for solution II (40,000 mg/L) were plotted in discontinuous lines with hollow marks. Three data series for each environment were plot-

ted for specimens with no prestrain ("No PreStrn"), with "PreStrn 1" (≈6%), and with "PreStrn 2" (≈12%). Corrosion rate results for alloy A was plotted in Fig. 4 and Fig. 5 for as received and stress relieved specimens. That was repeated for alloy B, as well, in Fig. 6 & Fig. 7.

4. Discussion

As shown in Fig. 4-7, the general trend of corrosion rate is the increase (slight) with time as far as equal time span readings for weight are taken. The longer the time period that specimens were immersed in the solutions, the lower the corrosion rate. That was regarded to the increased corroded film of the specimens' surface which constitutes protection against corrosion. That was indicated to in many references[19, 25-26].
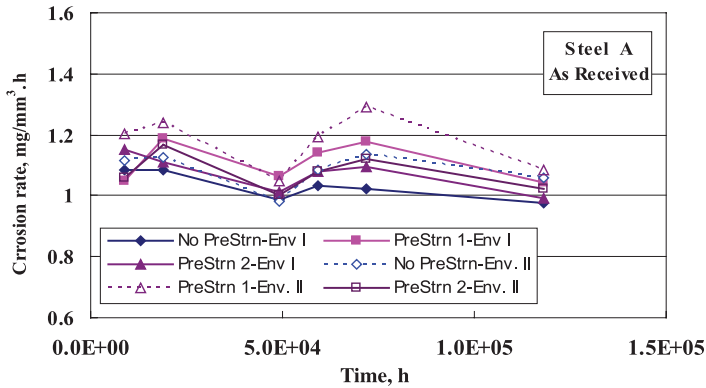

Fig. 4. Corrosion behavior of steel A as received.
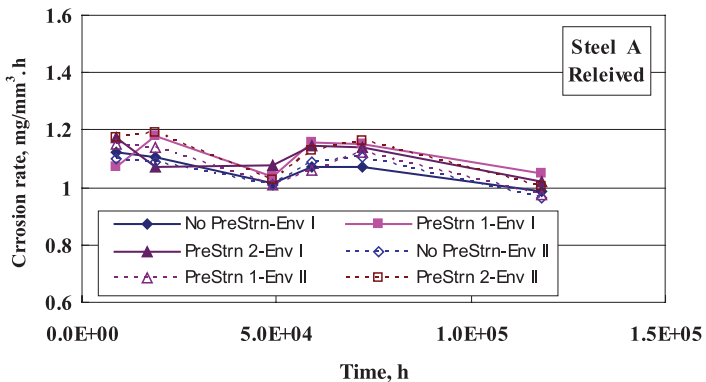**Environment I: 35,000 PPM (pH = 7.8) and Environment II: 40,000 PPM (pH=8)**

Fig. 5. Corrosion behavior of steel A, stress relieved.
Environment I: 35,000 PPM (pH = 7.8) and Environment II: 40,000 PPM (pH = 8)
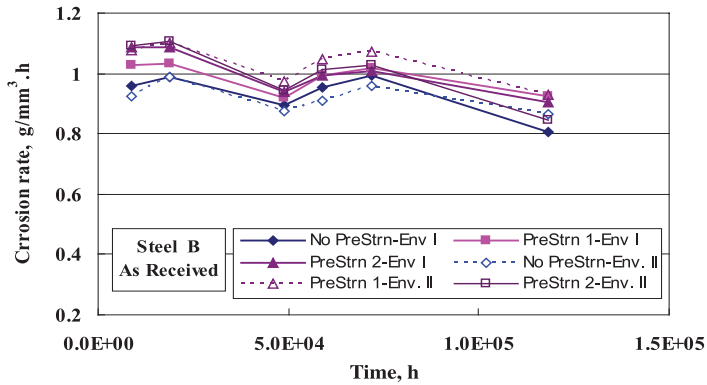
Fig. 6. Corrosion behavior of steel B as received.
Environment I: 35,000 PPM (pH = 7.8) and Environment II: 40,000 PPM (pH = 8)
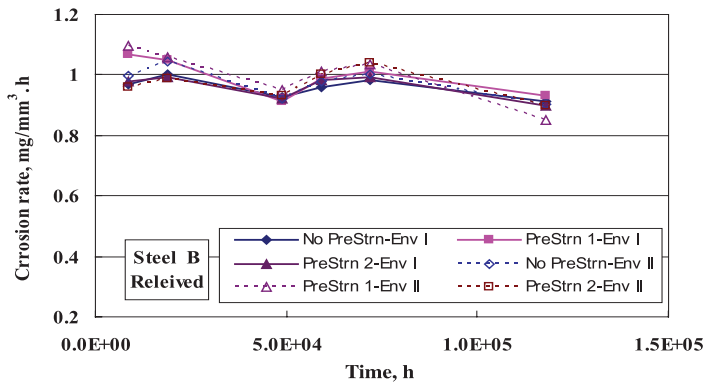

Fig. 7. Corrosion behavior of steel B, stress relieved.
Environment I: 35,000 PPM (pH = 7.8) and Environment II: 40,000 PPM (pH = 8)

The slowness in the corrosion rate was slightly time dependent (within the testing range) as was indicated by points 3 and 6 in all graphs. In other words, the longer the period of measurement (which involves surface cleaning) the thicker the corroded film, which leads to more protection against accelerated corrosion.

Prestraining for the two alloys led to a slight increase in corrosion rates for almost all specimens. That was also true for both solutions used for immersion. This may be attributed, as it was assumed at the beginning, to dislocation density. As the dislocation density increases, the locations inside the specimens and on their surfaces for different kinds of lattice imperfections increases. This leads to an increased number of locations where corrosion starts to develop. The work

done by Novak[22] and Mills *et al.*[23] was to use the prestraining on notched specimens to cause residual compressive stress that can help close the micro-cracks and crack which helps retarding stress corrosion cracking. Even though the prestraining can cause increased dislocation densities, still the presence of residual compressive stress in such situations can be much more effective in retarding stress corrosion and stress corrosion cracking. What supports this point of view is the increased corrosion rates associated with the specimens made without any treatment. When specimens were stress relieved, the corrosion rates were decreased for both alloys. Corrosive media constituted of lower salinity concentration (35,000 mg/L) showed very slight increase in corrosion rates compared with the higher salinity one. The effect of the corrosive media is slightly more obvious in the case of specimens made from "as received" bars of both alloys when compared with the stress relieved specimens.

Steel alloy with a higher carbon content (designated as A) showed noticeably higher corrosion rates compared with the other alloy (designated B). This may be attributed to the copper and silicon contents that are higher in alloy B compared with alloy B (Table 1). This is in consistence with the literature. The contribution to prestraining on the increase of corrosion rates was more obvious in alloy A compared with alloy B. This may lead to the importance of material composition rather than microstructure of the alloy (ferrite versus pearlite dominated structures) in corrosion resistance.

5. Conclusions

- Prestraining led to some slight increase in corrosion rates of reinforcing steel bars when compared with specimens without prestraining. This effect was more obvious at higher prestraining degrees for both alloys used for this study.
- Material composition is more important for determining corrosion rates when compared with microstructure of used alloys.
- Longer periods of immersion led to slower rates of corrosion for both alloys used in this study.
- Stress relieved specimens performed better compared with other specimens as far as the corrosion rate is considered. Lower corrosion rates were associated with stress relieved specimens.

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المستخلص.   تستخدم منتجات الحديد الصلب بكثرة في التطبيقات المعرضة للعوامل الجوية التي تساعد على التآكل، و ينشأ عن ذلك فقد في أبعادها وفقد في قوة تحملها. وتعاني منتجات حديد التسليح للخرسانات من نفس المشاكل نتيجة لتآكلها. وقد عني هذا البحث بدراسة إمكانية تأثير تعريض عينات حديد التسليح لإجهاد سابق (تسبيب تشوه دائم) على أدائه في مقاومة التآكل. وقد تم تعريض عينات من نوعين مختلفين لتشوه منتظم على مقطع العينة. وتم إحداث درجتين من الاجهاد المسبب لانفعال دائم في النوعين المستخدمين من حديد التسليح في الدراسة. ومن خلال الدراسة تم تعريض تلك العينات لنوعين من المحاليل بدرجتي تركيز مختلفتين واستخدمت طريقة الفقد في الوزن لعمل الدراسة وأخذ في الاعتبار أداء العينات التي أجرى لها إزالة للإجهادات المتبقية (Stress relieving) وتم عرض كل النتائج التي تم التوصل إليها ومناقشاتها في البحث. وفي المجمل فإن الانفعال المسبق للعينات أدى إلى بعض الزيادة في معدل التآكل وزاد من هذا التأثير زيادة كم الانفعال المسبق في العينات، ويلغى هذا التأثير إجراء معالجة حرارية لإزالة الاجهادات المتبقية في العينات.