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Original Article

Cathodic polarization behavior of the structural steel wires under different prestressing conditions

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ABSTRACT

Cold-drawn structural steel wires prestressed to different levels and cathodically polarized at various potentials were investigated using electrochemical techniques and slow strain rate tests. The potentiodynamic polarization revealed that prestressing enhances the active anodic dissolution of the structural steel wires. The corrosion current density and corrosion potential were observed to vary with prestressing levels applied to the structural steel wire specimens. The structural steel wire prestressed to 80% of its original tensile strength and cathodically polarized at -1500 mV exhibited the highest current densities and lowest corrosion potentials after potentiodynamic polarization, which indicate that the above prestressing and cathodic polarization conditions lower the corrosion resistance of the material. Moreover, the tensile results show that the structural steel wire prestressed to higher levels and cathodically polarized at lower potentials was more susceptible to degradation of the tensile properties. The structural steel wire prestressed to 80% level and cathodically polarized at a potential of -1500 mV exhibits the lowest UTS and ductility. The tensile fracture surfaces of the steel wires prestressed and cathodically polarized under above conditions exhibit mostly quasi-cleavage brittle fracture character. Furthermore, the brittle regions were observed to increase with increasing the prestressing levels and decreasing the cathodic polarization potentials applied to the structural steel wires.

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1. Introduction

Prestressing steel wires is employed in civil engineering for the prestressed concrete structures. The prestressing of the steel wires compensates the inadequate tensile strength as well as

prevents cracking of the concrete structure. The prestressed concrete structures have smaller deformation and can absorb more tension than those of non-prestressed concrete structure. Cathodic protection is applied to the prestressed concrete structure to protect the steel wires from corrosion. Corrosion of the prestressed steel wires leads to damage of the concrete

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structure. The damage of the concrete structure may be due to the hydrogen embrittlement of pre-stressing steel and bond strength between concrete and prestressing steel. It is well recognized that hydrogen is evolved on the surface of steel during cathodic protection at more negative potential [1]. The steel is protected against corrosion due to the formation of passive iron oxide film on the steel surface resulted from active polarization. The effect of cathodic polarization is depended on the applied stress level and the size of corrosion induced cracking [2]. The durability of the concrete structure is affected by unsuitable post-tension of the concrete components such as prestressing steel wires. The failure of the prestressed concrete structure is attributed to the corrosion induced cracking. It has been shown that the hydrogen embrittlement may occur in partially prestressed elements [3] and the fractures of prestressing steel are due to hydrogen-induced cracking or anodic stress corrosion [4]. It has been concluded that hydrogen may enter the tendons as a result of cathodic protection or the acidification of the solution within corroding pits [5]. The susceptibility of highest-strength steel to hydrogen embrittlement was confirmed by slow strain-rate tests using pre-cracked, specimens under various environment conditions [6]. The susceptibility of prestressing steels to hydrogen embrittlement can be determined by the ammonium thiocyanate test [7]. It is found that the high-strength steel fails because its notched-bar tensile strength in the region of corrosion pits has been exceeded and the failure type in this case is brittle [8]. The prestressing steel wire is produced from hot rolled steel, which has pearlitic microstructure. The hot rolled steel is subjected to cold deformation to increases the tensile strength of the steel wire. The pearlite bands prevent diffusion of hydrogen through the surface of the stress free steel [9]. However, the tensile stresses increase hydrogen ingress into the steel leading to drastic decrease of the local grain boundary resistance and progressive failure of the steel [10].

The current research investigates the effect of prestressing and cathodic polarization on the corrosion behaviors and tensile properties of the structural steel wire. The corrosion resistance of the structural steel wire was evaluated by potentiodynamic polarization tests and slow strain tensile testing was conducted to determine the tensile properties and fracture modes under the above prestressing and cathodic polarization conditions.

2. Experimental procedure

Structural steel wire of 5 mm diameter was used in the current investigation. The chemical composition of steel wire is listed in Table 1. The tensile specimens were machined from the steel wire with a dimension of 200 mm. The tensile steel wire specimens were heated to 200 °C in an electric resistance

Table 1 – Chemical composition of prestressing steel wire (wt%).

C	Mn	Si	Cu	P	S
0.83	0.69	0.21	0.27	0.011	0.0033

furnace for 30 min to remove the residual stresses generated from machining and then prestressed to 20%, 40%, 60% and 80% of its ultimate tensile strength. The tensile steel wire specimens were pickled in nitric acid to remove the oxidized layer.

Gamry PC4 potentiostat was used to conduct potentiodynamic polarization tests. The tests were performed in a corrosive solution of deaerated 3.5 M NaCl solution with pH 6.1, at a temperature of 25 °C. Argon deaeration of the solution was performed for 24 h before the potentiodynamic polarization tests. The steel wire specimens were immersed in corrosive solution for 20 min before starting of the measurements to reach a stable open circuit potential. Then the steel wire specimens were potentiodynamically polarized and scanned from the cathodic potential to the anodic potential at a scan rate of 0.2 mV/s. The electrochemical cell contains steel wire specimen as working electrode, platinum as counter electrode and saturated calomel as reference electrode (SCE).

Slow strain tensile test (SSRT) at strain rate of 10^{-6} s^{-1} in a solution containing $\text{Ca}(\text{OH})_2$ with NaCl was conducted on the prestressed steel wire specimens. The steel wire specimens were cathodically polarized at -500 , -1000 , -1250 and -1500 mV in the electrochemical cell of stainless steel mesh as counter electrode and saturated calomel electrode (SCE) as reference. The fracture surfaces were studied under scanning electron microscope (SEM) to determine the fracture modes of the prestressed and cathodically polarized steel wire specimens.

3. Results and discussion

3.1. Polarization behaviors of the prestressing structural steel wires

Active anodic dissolution and Tafel behaviors were observed during potentiodynamic polarization of prestressing structural steel wires to various levels. However the active anodic dissolution was found to vary with the level of prestressing applied to the steel wire. This indicates that the prestressing procedure has a pronounced effect on the corrosion of the structural steel wires. Thus, the potentiodynamic polarization shows that the prestressing procedure enhances the active anodic dissolution of the structural steel wires as can be observed from Fig. 1. The corrosion potentials and

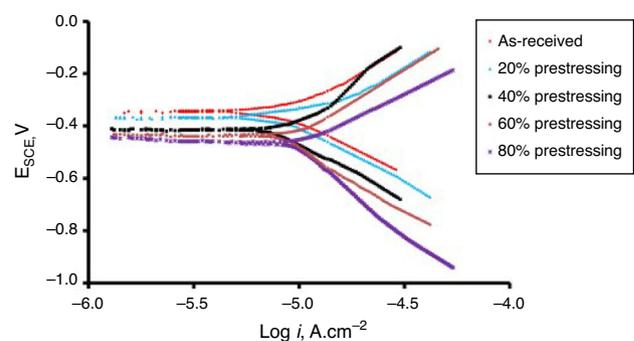


Fig. 1 – Potentiodynamic polarization curves of the as-received and prestressed structural steel wire specimens to various levels.

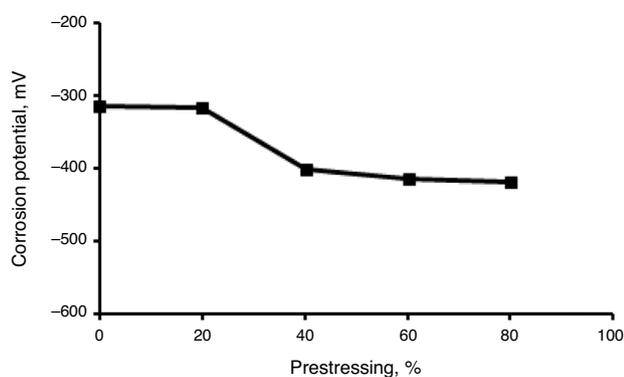


Fig. 2 – The effect of prestressing on the corrosion potential of the structural steel wires.

current densities determined from the polarization curves of the as-received and the prestressing structural steel wires confirm the above observations. The effect of prestressing on the corrosion potential of the structural steel wires is shown in Fig. 2. As can be seen from this figure, the prestressing results in the decrease of the corrosion potential of the structural steel wires. The corrosion potential of the steel wire specimen prestressed to 20% is slightly lower than that of the non-prestressed one, which indicate clearly that the above prestressing condition has no or slight effect on the corrosion potential of the steel wire specimen. However, the significant effect of the prestressing was observed on the steel wire specimens prestressed above 20% as can be seen from Fig. 2. Thus, the corrosion potential for the steel wire specimen prestressed to 80% is -419 mV , which is much lower than that of the non-prestressed one. The corrosion potential of the steel wire specimen prestressed to 80% is almost one and one-third lower than that of the quenched non-prestressed specimen (see Table 2).

The corrosion current density was found to vary with the prestressing conditions applied to the steel wires. The highest corrosion current density was observed in the steel wire specimen prestressed to 80%, which indicate that the former specimen has the lowest corrosion resistance. Thus the corrosion current density of the steel wire specimen prestressed under above condition is $15.81\ \mu\text{m}/\text{cm}^2$, which is much higher than that of the non-prestressed one. It is about one and half times higher than that of the non-prestressed steel wire specimen. The corrosion current density of the steel wires as a function of prestressing levels is shown in Fig. 3. As can be seen from this figure, the higher the prestressing level applied to the steel wires, the higher the corrosion current density. The

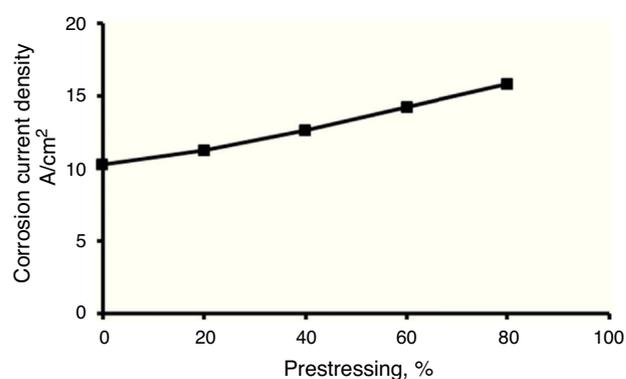


Fig. 3 – The effect of prestressing on the corrosion current density of the structural steel wires.

above experimental findings show that the prestressing lowers the corrosion resistance of the structural steel wires. The low corrosion resistance found in the prestressing steel wire specimens may be attributed due to lattice defects and residual stresses generated during prestressing of the steel wires. The defects resulted from prestressing become initiation sites for corrosion.

3.2. Tensile behaviors of the cathodically polarized prestressing quench steel wires

The tensile properties of the prestressing structural steel wire specimens and then cathodically polarized at various potentials were evaluated to clarify the influence of such conditions on the performance of the material. The tensile test results of the prestressing steel wires exhibit different performance depending on the cathodic polarization conditions applied to the material. The tensile response of the steel wires under these cathodic polarization conditions was compared to that of the non-cathodically polarized wire. The stress-strain diagrams of the structural steel wires prestressed to 80% and then polarized at various cathodic potentials are shown in Fig. 4. The ultimate tensile strengths (UTS) of the prestressed and then cathodically polarized structural steel wire specimens are lower than that of the non-cathodically polarized and non-prestressed specimen. The steel wire specimen prestressed to 80% and then cathodically polarized at a potential of -1500 mV exhibits the lowest UTS among other specimens polarized at a higher cathodic potentials. The degradation of the tensile strengths observed in the steel wire specimens prestressed to a high level and then polarized at a lower cathodic potential is believed to be due to the stresses generated into them during prestressing and the ingress of hydrogen during cathodic polarization. A direct relationship between the cathodic polarization potential and the degradation of the tensile properties of the structural steel wire was noted during the above tests. A significant decrease in the tensile properties was observed in the steel wires prestressed to 80% level and cathodically polarized at -1250 and -1500 mV potentials.

The effect of the cathodic polarization potential on the UTS of the steel wire specimens prestressed to 80% level is shown in Fig. 5. The experimental results show that at above -1250 mV cathodic potentials, the UTS of the steel wire

Table 2 – The corrosion parameters of the structural steel specimens as a function of prestressing.

Prestressing %	E_{corr} , V	i_{corr} , $\mu\text{A cm}^{-2}$
0	-0.314	10.23
20	-0.318	11.22
40	-0.402	12.6
60	-0.414	14.21
80	-0.419	15.81

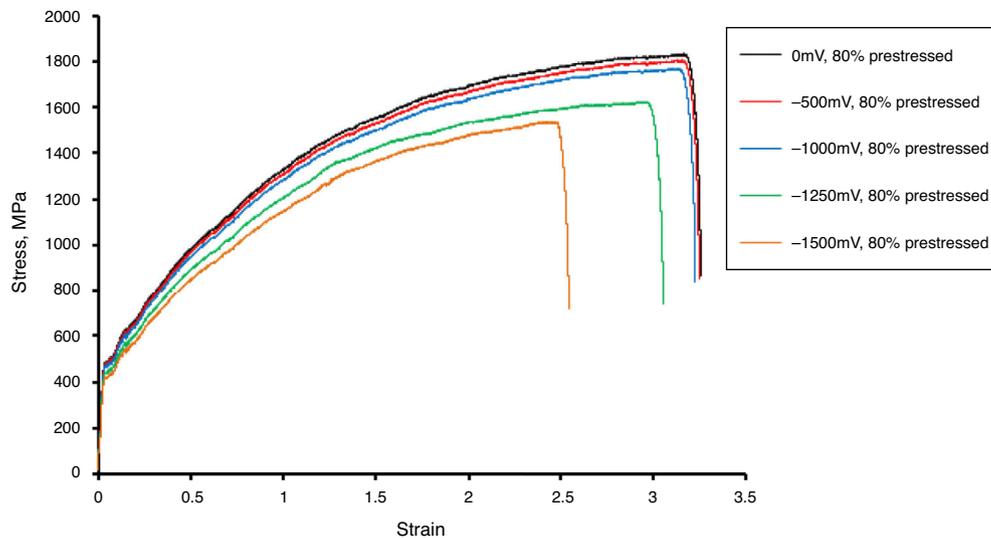


Fig. 4 – The stress–strain diagrams of the cathodically polarized prestressing steel wire specimens at different potentials.

specimens are slightly affected by the cathodic polarization, however, beyond the above cathodic potentials, the UTS significantly were decreased. The steel wire specimen prestressed to 80% level and cathodically polarized at -1500 mV potential shows a 17% decrease in the UTS while an 11% decrease in the UTS of the specimen polarized at a higher cathodic potential (i.e. -1250 mV) was observed. The more decrease in the UTS of the steel wire specimen prestressed to 80% level and then cathodically polarized at -1500 mV potential is attributed to more hydrogen generated during the former cathodic polarization condition. The hydrogen is generated during cathodic polarization of the prestressing steel wire as a result of cathodic reaction, which can be either reduction of oxygen or reduction of water molecules [4].

The ductility of prestressing steel wire was determined by measurements of the reduction of area before and after cathodic polarization. The ductility of the steel wire specimens was observed to be a unique function of cathodic polarization potential. As can be seen from Fig. 6, the reduction of area is decreased with decreasing the cathodic polarization potential applied to the prestressing steel wire specimens.

A significant decrease in the reduction of area was found at lower or more negative cathodic polarization potentials. It can be seen from Fig. 6 that approximately 21% decrease in the reduction in area of the steel wire specimen prestressed to 80% level and cathodically polarized at a lower or more negative potential (i.e. -1500 mV), which is higher than that of the prestressing steel wire specimen polarized at a higher or more positive cathodic potential (i.e. -1250 mV), which is 26%. At higher or more positive cathodic polarization potentials than the above potentials, no significant decrease in the reduction of area of the steel wire specimens was found.

The decrease of the reduction of area observed in the steel wire specimens cathodically polarized at more negative potentials is believed to be due to generation of more hydrogen during cathodic polarization as stated previously. It has been proposed that the atomic hydrogen is dissolved in the material lattice and concentrated near slip dislocation sites. The dissolved hydrogen interferes with the slip mechanism, which results in decreasing the ductility of the material.

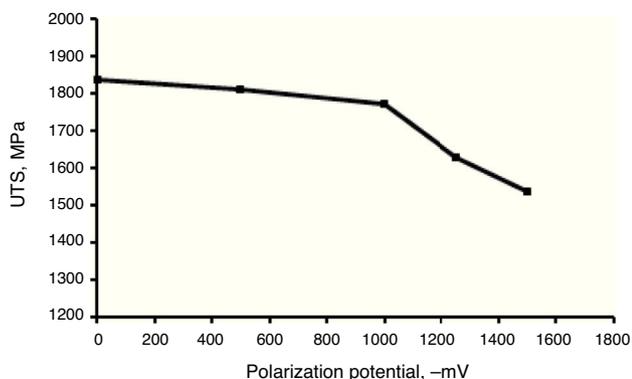


Fig. 5 – The effect of cathodic polarization potential on the UTS of the prestressing steel wire specimens.

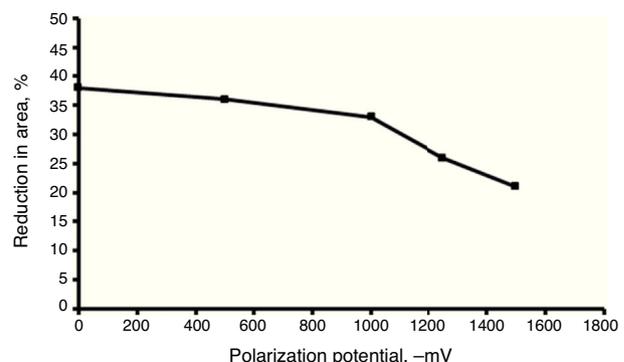


Fig. 6 – The reduction in area of the prestressing steel wire specimens as a function of cathodic polarization potential.

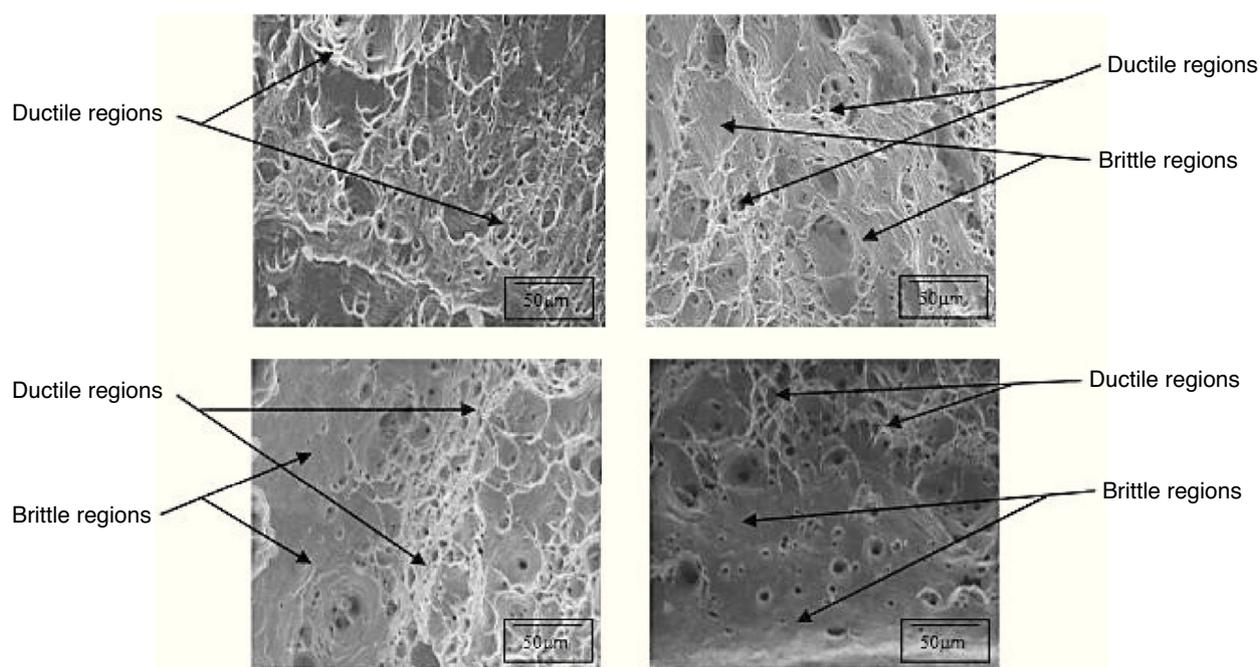


Fig. 7 – Fracture surfaces of steel wire specimens prestressed to 80% (a) non-cathodically polarized and cathodically polarized at potentials of (b) -1000 mV, (c) -1250 mV and (d) -1500 mV.

3.3. Tensile fracture of the cathodically polarized prestressing steel wires

Fractographic examinations of the cathodically polarized prestressing structural steel wire specimens revealed that the modes of fracture depend on the cathodic polarization conditions applied to the material. The structural steel wire specimens were prestressed to 80% of their UTS and then polarized at different cathodic potentials. The fracture surface of the non-polarized prestressing steel wire specimen exhibits ductile with dimple appearance (Fig. 7(a)). No significant changes in the fracture modes of the prestressing steel wire specimens which have been cathodically polarized at -500 and -1000 mV potentials was observed. The fracture modes of the above prestressing steel wire specimens show also predominantly ductile microvoid coalescence fractures after cathodic polarization, which clearly demonstrate that cathodic polarization conditions at below -1250 mV have no effect on the failure mode of the prestressing structural steel wire specimens, as can be seen from Fig. 7(b) and (c). It is believed that at the above cathodic polarization conditions (i.e. below -1250 mV), the prestressing structural steel wire specimens absorb the lowest hydrogen concentrations which prevent changes in the fracture modes. However, the cathodically polarized prestressing steel wire specimens at more negative potentials fractured in different modes of failure. The fracture surface of the prestressing structural steel wire specimen shows mixed mode of fracture i.e. quasi-cleavage and microvoid coalescence (Fig. 7(d)) after cathodic polarization at -1250 mV potential. The change of the fracture mode observed at the fracture surface of the structural prestressing steel wire specimen cathodically polarized at a potential of -1250 mV may be due to a higher concentrations of the

hydrogen absorbed by the above specimen during the above cathodic polarization condition.

4. Conclusions

The influence of the prestressing and cathodic polarization conditions on the structural steel wires was studied throughout the current investigation. The following conclusions can be made from this investigation:

1. The prestressing has significant effect on tensile response as well as the corrosion resistance of the cathodically polarized steel wires.
2. The lower the cathodic polarization potential and the higher prestressing level, the lower the mechanical properties and the corrosion resistance of the structural steel wires.
3. The mode of failure was found to depend on the cathodic polarization and prestressing conditions applied to the material. The structural steel wires prestressed to higher levels and polarized at lower cathodic polarization potentials fractured mostly in brittle manner.

Conflicts of interest

The authors declare no conflicts of interest.

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