UDK 620.193:691.328

SUSCEPTIBILITY OF PRESTRESSING STEEL WIRES TO HYDROGEN ASSISTED CRACKING IN ALKALI MEDIUM SIMULATING CONCRETE PORE SOLUTION

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Susceptibility to hydrogen assisted cracking of cold drawn pearlitic steel wires used as a concrete reinforcement is studied in an alkali environment modelling pore liquid in concrete. Prestressing steel is established to become susceptible to hydrogen embrittlement under potentials –1.1 V (SCE). The maximum fracture load as well as elongation to fracture decrease with cathodic potential increment, the effect is more notable under slow strain rate. Fracture mechanism in aggressive medium differs from that in air. The role of surface defects in the environment assisted cracking is discussed.

Keywords: *prestressing steel, reinforced concrete, hydrogenation, surface defects.*

Intensive corrosion of reinforced concrete structures such as bridges and car park decks during their long-term service can be attributed to the prolonged exposure of these structures to a chloride-contaminated environment, i.e. marine structures or through the application of de-icing salts. Although concrete carbonation also leads to reinforcement corrosion because of reducing of its alkalinity, presence of chlorides is the most important factor which determines corrosion resistance of reinforcement [1]. These ions penetrate into the concrete cover and eventually reach the reinforcement where corrosion starts once a critical chloride threshold is exceeded. Corrosion results in thinning of steel wires and simultaneous expansion of corrosion products which leads to spalling of concrete cover. Due to electrochemical nature of reinforcement corrosion in concrete, the most effective methods of rehabilitation are also electrochemical, namely, cathodic protection, cathodic prevention or electrochemical chloride extraction. Additionally, the alkalinity of carbonated concrete can be restored using re-alkalization [2]. Most of the RC structures contain prestressed elements such as slabs or beams and the application of electrochemical rehabilitation techniques to these elements would lead to savings through the extension of their service life. On the other hand, prestressed concrete contains high-strength steel reinforcement which is suggested to be susceptible to hydrogen embrittlement, therefore a possible risk of hydrogen-induced stress corrosion cracking could not be neglected.

Earlier investigations of prestressing pearlitic steel using both preckracked and notched specimens proved its high susceptibility to hydrogen assisted cracking [3–5]. The essential role of residual stresses and a concentrator shape were established, and the hydrogen diffusion model including the effects of both hydrogen concentration and hydrostatic stress distribution was proposed to explain environmental and hydrogenation effects on the pearlitic steel [3, 4].

Environmental effects on the smooth prestressing wires fracture have been studied insufficiently comparing to the notched and pre-cracked ones. Among the researches concerning as-received wires it is difficult to distinguish some clear regularity, but these data are of interest because the wires are put in the concrete just in such a state.

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The investigations of the prestressing pearlitic steel carried out in the wide range of potentials, pH and under different strain rates were presented in paper [5]. Strain rate of about $5{\cdot}10^{-7}$ s^{-1} produced evidence, in the form of the reduction in area and maximum load, of environment sensitive fracture. However the trends were not invariably systematic with respect to the different exposure conditions and the maximum loads achieved in all of the tests were very similar, and again showed no strictly systematic variation.

One of the most widely used methods for assessment of the hydrogen effect on the steel reinforcement is the FIP Test Method (UNE 36-464-86), however it also leads to a broad experimental scatter. Presence of the surface defects and the residual stresses may affect the results [4, 6].

The aim of the research is to clarify the trends in hydrogen assisted fracture of the prestressing steel wires and the role of surface defects in the process.

Materials and methods. Commercial pearlitic steel used in experiments was supplied in the form of cold drawn wires which had passed through seven cold drawing steps to attain the final diameter of 5.04 mm. Its chemical composition is the following (wt.%): 0.789 C; 0.681 Mn; 0.210 Si; 0.010 P; 0.008 S; 0.218 Cr; 0.003 Al; 0.061 V; Fe is balance. Plastic strain accumulated by steel due to the cold drawing process $\varepsilon^{P}_{\text{accum}} = 2\ln(D_0 / D_i)$ is equal to 1.57. Hydrogen embrittlement of the prestressing steel was investigated by slow strain rate testing (SSRT) (10^{-6}…10^{-7} s^{-1}) using smooth steel wires in as-received state. Surface of the tested wires was not grinded but only degreased with acetone and washed with water to bring them closer to the real working conditions. Specimens were tested on the MTS Alliance RT/100 testing machine with software TESTWORKS 4. The initial distance between grips was 220 mm. Corrosive environment containing 1 g/l $Ca(OH)_2$ and 0.1 g/l NaCl (pH 12.5) reproduced alkaline working medium (pore liquid) in concrete [5, 7]. An electrochemical cell of 8 mm height was fixed around a specimen. The standard three-electrode scheme was used to apply cathodic polarization to the tested wires in the range of –1.1…–1.4 V (SCE) and the potentiostat AMEL VOLTALAB PGP 201. At least three specimens were tested for each experiment.

Results and discussion. It is obvious from the load-displacement curves that the prestressing steel is susceptible to hydrogen embrittlement under cathodic polarization (Fig. 1). Essential changes in steel mechanical behaviour have been detected at the potential –1.1 V and lower. Hydrogenation does not influence the yield strength while ultimate tensile strength is not reached due to hydrogen action.

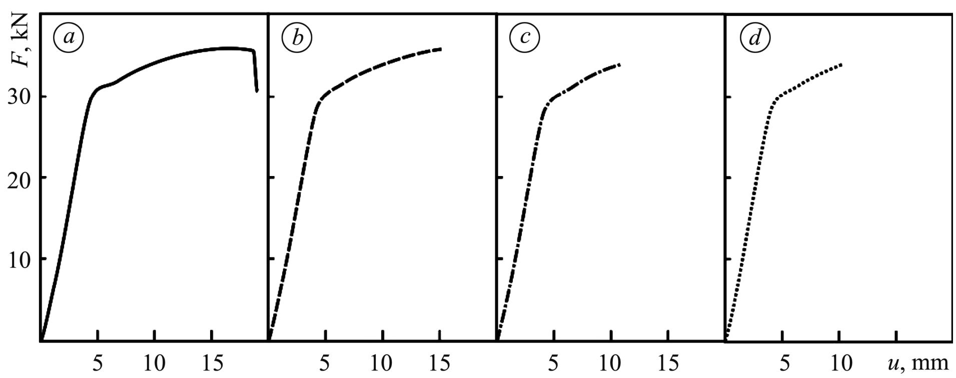

Fig. 1. Load-displacement curves of the prestressing steel in the medium containing 1 g/l $Ca(OH)_2$ + 0.1 g/l NaCl (pH 12.5) in air (*a*) and under cathodic polarization: –1.1 V (*b*), –1.2 V (*c*), –1.4 V (*d*); strain rate $7.5{\cdot}10^{-7}$ s^{-1}.

The effect of cathodic polarization on the mechanical characteristics, namely, elongation and fracture load of pearlitic cold drawn steels is shown in Fig. 2. For the both parameters this effect is more pronounced under lower strain rate because in this case hydrogen has more time to affect a metal. Under high strain rate the effect of hydrogen on such type of steels is negligible even under polarization of –1.5 V [5]. It is established also that resistance of high strength pearlitic steels to hydrogen assisted cracking is higher than martensitic ones of the same strength [8]. Comparatively low (as for a high strength steel) hydrogen propensity of cold drawn pearlitic wires can be explained by several factors: specific microstructure with little grains and diminutive distances between ferrite and cementite lamellae; low hydrogen diffusion coefficient ~10^{-12} cm/s; compressive stresses at the wires surface produced by cold drawing process which suppress hydrogen uptake.

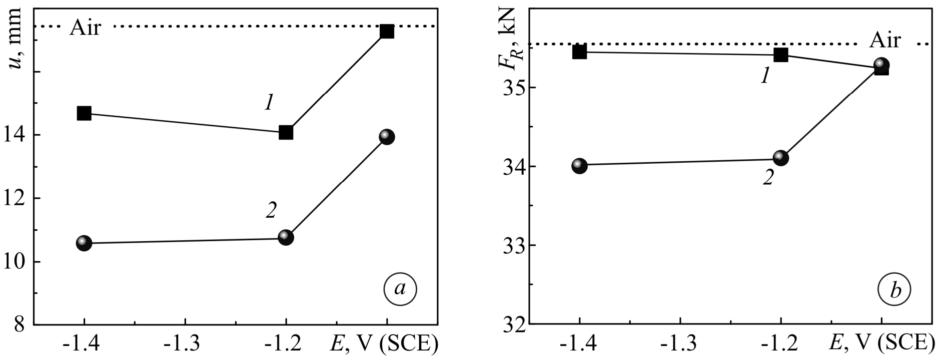

Fig. 2. Change in elongation to fracture u (*a*) and maximum load to fracture F_R (*b*) of the prestressing steel in SSRT under cathodic polarization with different strain rates: *1* – $7.5 \cdot 10^{-6}$ s^{-1}; *2* – $7.5 \cdot 10^{-7}$ s^{-1}.

In the wires tested in as-received state, surface defects become very important since they are stress concentrators and the primary sites of hydrogen uptake. There are two main types of surface defects [9]: defects produced by cold drawing process itself or due to transformation of those presented in a row material (hot rolled bar) (Fig. 3*a*); voids created in the sites of nonmetallic inclusions near the surface (Fig. 3*b*).

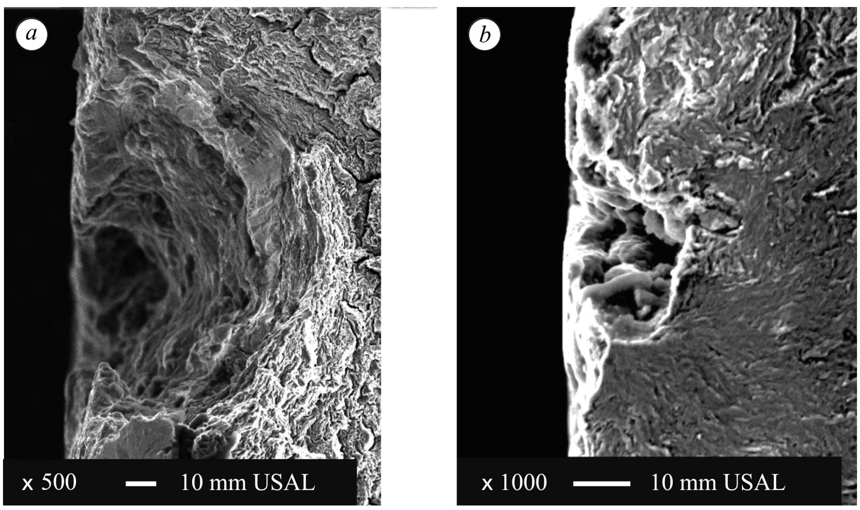

Fig. 3. Types of surface defects on the prestressing pearlitic steel.

It is shown that the defects of type 2 usually have hemispherical shape with a depth of about 25 μm [9]. These defects can be formed as a result of cold drawing or due to transformation of those created previously in the hot rolled steel. Evidently, fracture in aggressive medium begins from one of these defects (Fig. 4*b*), in contrast to the fracture in air (Fig. 4*a*).

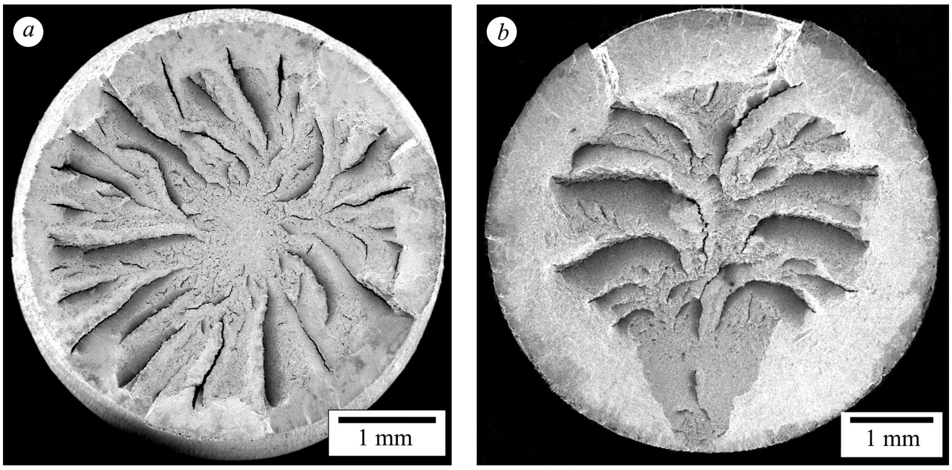

Fig. 4. Fracture maps of the prestressing pearlitic steel after the test in air [10] (*a*) and in alkali medium (pH 12.5) under cathodic polarization –1.2 V (SCE) with a strain rate $7.5{\cdot}10^{-7}$ s^{-1} (*b*).

The precise analysis at a microscale of the fracture surface of the specimen after the test under cathodic polarization reveals some features of brittle fracture in the centre of the specimen fracture surface, namely, separate circular cleavage facets (appeared due to hydrogen action [11]) against a background of microvoid coalescence relief (Fig. 5).

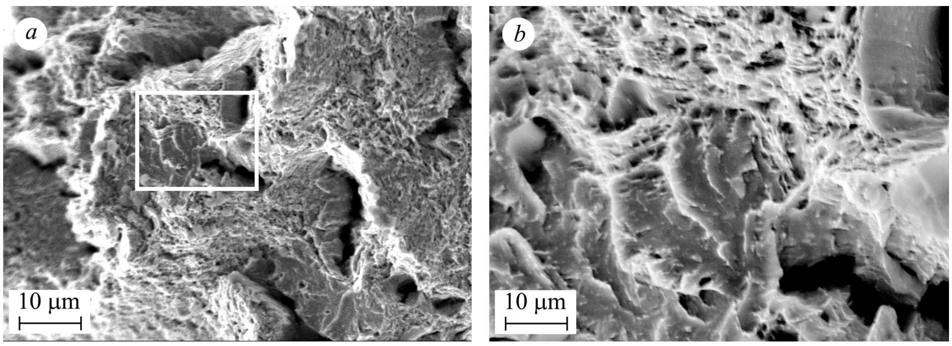

Fig. 5. Fracture surface of the prestressing steel wire central zone after the tensile test under hydrogenation in the solution with pH 12.5 (*a*) and its details (*b*).

It should be noted that all tensile curves (both in air and environment) exhibit the same trend (Fig. 1), which confirms a suggestion that some cracks may nucleate in the centre of wires cross-section as a result of the combined effect of applied stresses, residual tensile ones (produced by cold drawing), and hydrogen uptake. Therefore nucleation and growth of cracks are most likely to occur simultaneously in different locations, in the central part of the specimen cross section and near its outer surface, finally merging by microvoid coalescence. Obviously, multiple initiations of surface cracks in initially smooth specimens contribute to the process, and the tendency exists for the fracture path to follow longitudinal routes between these cracks when the latter do not lie in essentially the same transverse plane [5]. However more investigations, primarily fractographic, are required to clarify the fracture peculiarities in smooth wires made of cold drawn pearlitic steel and the role of surface defects in it.

CONCLUSIONS

Cold drawn pearlitic steel is susceptible to hydrogen assisted cracking under applied potential of –1.1 V (SCE) and below, but this effect reveals itself only under low (~10^{-7} s^{-1}) strain rate. In contrast to the tensile test in air, fracture of the steel wires in the aggressive medium is caused by simultaneous nucleation of cracks in the central part of the specimen cross section and near its outer surface.

РЕЗЮМЕ. Досліджено закономірності механічної поведінки арматурних прутків з перлітної сталі, зміцнених холодним волочінням, за їх повільного розтягу у лужному середовищі, яке моделює рідину в порах бетону. Схильність сталі до водневого окрихчення проявляється за наводнювання під час навантаження при потенціалі нижче –1,1 V. За інтенсифікації катодної поляризації максимальне напруження до руйнування, а також видовження зразків знижуються, суттєвіше за нижчої швидкості деформування. Проаналізовано фрактографічні відмінності зламів зразків на повітрі та в середовищі за наводнювання і обговорено вплив на їх руйнування поверхневих дефектів.

РЕЗЮМЕ. Исследованы закономерности механического поведения арматурных прутков из перлитной стали, упрочненных холодным волочением, при их медленном растяжении в щелочной среде, которая моделирует жидкость в порах бетона. Подверженность стали водородному охрупчиванию проявляется при наводороживании в процессе нагружения при потенциале ниже –1,1 V. Максимальное напряжение до разрушения, а также удлинение образцов, снижаются при более интенсивной катодной поляризации, существеннее при более низкой скорости деформирования. Проанализированы фрактографические отличия поверхностей изломов образцов на воздухе и в среде при наводороживании и рассмотрено влияние на их разрушение поверхностных дефектов.

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Received 20.06.2016