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ANALYSIS OF THE PLASTICITY CHARACTERISTICS OF PROGRESSIVELY DRAWN PEARLITIC STEEL WIRES

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Changes in the plasticity characteristics in air and in a hydrogenating environment of prestressing steel wires due to cold drawing process are investigated on the basis of slow strain rate tests on smooth specimens. The tested pearlitic steel is highly susceptible to hydrogen embrittlement at all stages of cold drawing. The inconsistency is revealed between the changes of two plasticity characteristics: reduction in area and uniform elongation. The obtained results are analysed distinguishing the contribution of resistance to crack initiation and crack propagation. Susceptibility to crack initiation increases as a result of cold drawing with simultaneous improvement of the crack propagation resistance.

Keywords: *prestressing steel, plasticity parameters, crack initiation and propagation.*

Prestressed concrete structures are a very important part of infrastructure of any country. They include buildings, transportation network, energy production, nuclear power plants, water and waste-water treatment systems etc. There is a lot of long-term service objects that have been in operation for 50 years and more. Their increasing age, the environmental impact, increasing traffic loads may change their serviceability [1]. Damage during service, frequently appearing after several years or decades of exploitation, is usually most consequential. The lack of sufficient protection resulting from the alkaline nature of the cement matrix in as-received state or the loss of alkalinity due to carbonation and/or depassivation caused by the chloride attack are the major causes of corrosion initiation. Failures of prestressing steel in structures are predominantly attributed to hydrogen-induced stress corrosion cracking [1] under simultaneous action of aqueous corrosive environment and static tensile stresses. In such conditions not only concrete coating fracture occurs but also prestressing steel wires could suffer in-service degradation similarly to other steels [2–5].

Mechanical behaviour and fracture peculiarities of prestressing steels under different environmental conditions have been studied thoroughly using both notched and pre-cracked specimens [6–9], paying attention to the stress state in the vicinity of the crack tip [7–9]. Meanwhile, there is a lack of data concerning smooth specimens and they are not clear/monosemantic due to a big scatter of results [6, 10]. This paper is aimed at fulfilling this gap and finding out some regularities of hydrogenation effect on cracks initiation and propagation in the prestressing steel wires without pre-cracking.

Materials and methods. Materials used were cylindrical specimens of cold drawn pearlitic steel wires from different steps of the real manufacturing process, and also the initial hot rolled steel bar. The steel conventionally called E, which passes through seven cold drawing steps has been studied. The chemical composition of the steel is the following (mass.%): 0.88 C, 0.69 Mn, 0.22 Si, 0.010 P, 0.024 S, 0.239 Cr, 0.076 Ni, 0.010 Mo, 0.129 Cu, 0.118 V, Fe is balance. Plastic strain $\varepsilon^{P}_{\text{accum}} = 2\ln(D_0 / D_i)$ accumulated by steel at each stage of the cold drawing process and corresponding diameter

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of the wires are shown in the Table. The hot rolled bar was marked E0 and the following steels as E1…E7 according to a cold drawing step.

Diameter *D* of the steels E and accumulated plastic deformation level ε^{p}_{accum}

Steel	E0	E1	E2	E3	E4	E5	E6	E7
D, mm	11.03	9.90	8.95	8.21	7.49	6.80	6.26	5.04
ε^{p}_{accum}	0.00	0.22	0.42	0.59	0.78	0.97	1.13	1.57

Mechanical investigations consisted in slow strain rate testing (10^{-7} s^{-1}) in air and in a model environment using smooth cylindrical specimens with diameters equal to wires thickness and with length 300 mm. Surface of the tested wires was not grinded but only degreased by acetone and washed with water to approach 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.

For the study of hydrogenation effect on the mechanical behaviour of the steel an electrochemical cell of 8 mm height was fixed around a specimen. In this electrochemical three-electrode scheme a tested wire (working electrode) was connected to a potentiostat by its negative pole and served as cathode. The platinum spiral as a counter electrode was used for polarization providing uniform distribution of current along the specimen surface. Constant cathodic potential –1.2 V was maintained by the potentiostat AMEL VOLTALAB PGP 201. Reference electrode was saturated calomel – SCE ($Hg|Hg_2Cl_2$). Tests were performed in the solution containing 1 g/l $Ca(OH)_2$ + 0.1 g/l NaCl (pH 12.5) with free oxygen access modelling a pore solution in concrete [6, 11]. At least three specimens were tested in air and for each “metal–environment” system.

The object of the analysis was the true stress– true strain curves σ–ε and reduction in area (RA), ψ. Curves in air were recorded using an extensometer and presented up to the moment of reaching the ultimate tensile strength σ_{UTS} (the stage of uniform elongation). For the tests in hydrogenating medium the whole tensile curves are shown. Percentage of RA was calculated after fracture of the specimens. The commercial wire was not taken into consideration because of its thermal treatment after cold drawing to remove residual stresses, which modified its plasticity characteristics. It did not allow the comparison of the final stage of cold drawing with the previous ones. Macrofracture maps were obtained using scanning electron microscope JEOL JSM-5610 LV for the identification of characteristic fracture zones, namely, crack initiation, subcritical crack growth and final fracture area.

Results and discussion. Uniform elongation ε_u of the specimens tested in air decreased sequentially with cold drawing degree with improving the strength characteristics (Fig. 1, curves *0*–*6*). Such mechanical behaviour corresponds to conventional notion about strain hardening of materials. Concerning the tests with cathodic polarization (Fig. 1, curves *0′*–*6′*), it should be noted that no visible transformations were fixed related to subcritical crack growth, because it could be reflected in the curves shape. It can be explained by a very low strain rate. In this case even if the stage of crack propagation is prolonged it could be visible in the negligible increment of ε on the stress–strain diagram. Hydrogenated material revealed divergent behaviour: firstly the parameter ε increased with cold drawing reaching the maximum value for the steel E3 and then it reduced. The possible explanation will be done later involving another plasticity parameter, reduction in area.

Reduction in area for the test in air, in contrast to relative elongation, is nonmonotonic function of accumulated plastic strain ε^{p}_{accum} exhibiting maximum at the later stages of cold drawing (Fig. 2, curve *1*). It means that two plasticity parameters, ε_u and

ψ, the former showing uniform deformation, and the latter – general plasticity under fracture, revealed opposite tendencies with ε^{p}_{accum} increment.

On the basis of the principle of volume constancy of a metal during its plastic deformation, it is possible to calculate its RA at the moment of reaching the σ_{UTS} value, ψ_u, using well-known relation [12]:

$$\varepsilon = 2\ln\frac{1}{1-\psi}. \qquad (1)$$

Since ε_u used for calculation corresponds to the start of a neck formation because of the crack nucleation inside a specimen, the obtained value ψ_u could be considered as an indirect indicator of steel resistance to crack initiation under tension. Values calculated for the tests in air are plotted in Fig. 2 as curve *2*. Thus, these data actually represent the material resistance to crack initiation which is relatively low for the tested steel.

Likewise the subtraction $\psi - \psi_u$ could characterise the stage of crack propagation – the greater this value, the higher the plasticity margin of material. Thereby ψ_u and ($\psi - \psi_u$) could be indicators of steel resistance to crack initiation and crack growth correspondingly. Analysis of Fig. 2 (curves *1* and *2*) reveals an opposite trend in the changes of these values. Regularities at the stage of crack initiation correspond to the expected results (ε_u decreases with cold drawing), while a positive effect of the steel treatment on crack growth resistance could be found in the peculiarities of metal structure changes due to cold drawing.

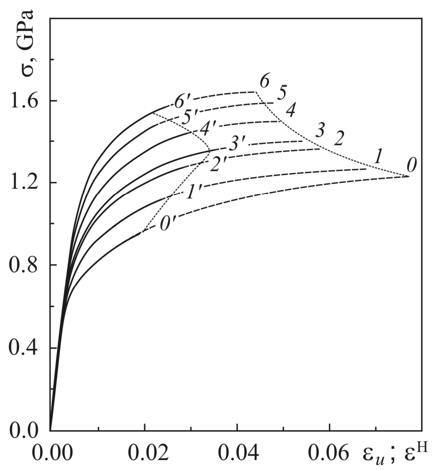

Fig. 1.

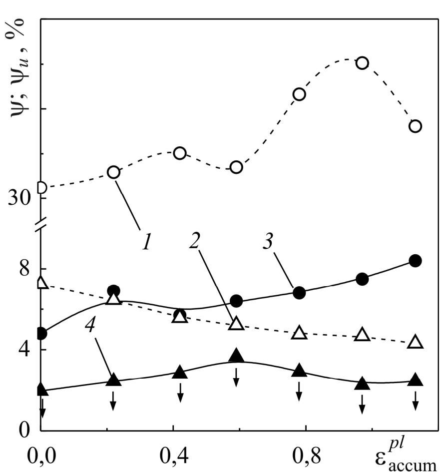

Fig. 2.

Fig. 1. Stress-strain curves of steel E in air (*0–6*) and under hydrogenation (*0'–6'*). The numbers indicate the cold drawing steps of the steel.

Fig. 2. Plasticity of the tested steel in air (*1*, *2*) and under cathodic polarization (*3*, *4*):
1, *3* – experimentally obtained reduction in area;
2, *4* – uniform reduction in area calculated from (1).

The foregoing approach to the plasticity parameters analysis was used also for the test results of hydrogenated specimens. In contrast to the test in air, stably low values of reduction in area ψ^{H} were obtained under hydrogenation conditions (Fig. 2, curve *3*), revealing high sensitivity of the tested steel to hydrogen embrittlement, previously described in [7]. Such behaviour was explained by progressive pearlite lamellas re-orientation in a direction parallel to the longitudinal wire axis at each step of cold drawing [8]. The maximum plasticity (in terms of ψ) corresponds to the total re-orientation of structural units, and from this point the following increment of plastic strain only reduces the parameter ψ.

Considering the wires suffering hydrogenation it was easy to note that fracture in all cases took place before reaching σ_{UTS}, obviously, due to rapid growth of a macro-crack. Therefore it could be assumed that values of rupture stress and stress for crack initiation were very close, the corresponding strain values ε^{H}_{u} being slightly less than ε^{H}. It could be accepted that $\varepsilon^{H}_{u} = \varepsilon^{H}$ to simplify the calculation. Then according to (1), curve *4* in Fig. 2, demonstrating the resistance of the investigated steels to initiation of hydrogen induced cracking, was obtained. The curve exhibited maximum in the middle stage of cold drawing, caused by a combined action of two competitive effects. Some retardation of crack initiation from the surface could be a result of reduced surface roughness as a result of cold drawing. Meanwhile, susceptibility to hydrogen assisted cracking prevails at the final stages because of considerable increment in steel strength. Obviously, surface roughness doesn't matter in the case of fracture in air, therefore the parameter ψ_u decreases sequentially with cold drawing degree (Fig. 2, curve *2*). Concerning the resistance to crack propagation under cathodic polarization $\psi^{H} - \psi^{H}_{u}$ (see Fig. 2, curves *3* and *4*), it should be noted that evolution of this parameter due to cold drawing is similar in both experimental conditions (air and hydrogenation) – it rises slightly at the later stages of cold drawing process. Another situation could be expected for the final prestressing steel (which is not considered in the present work) due to its extremely high strength and essential susceptibility to hydrogen embrittlement [7].

Examples of typical fracture maps after both tests (in air and under cathodic polarization) are presented in Fig. 3. Three characteristic zones should be distinguished on the fracture surface of the specimen broken in air: a central zone, an intermediate zone and a shear lip. For the hydrogenated specimen all three zones were also present. Besides, a new zone appeared, called tearing topography surface (TTS), and reported previously in [9], which is situated near the lateral surface and indicates the place of crack initiation. In both cases radial marks in the intermediate zone were observed which indicated crack growth direction – from the centre of each specimen to its edge. It is derived from the comparison of the presented fracture maps that, despite of the appearance of TTS (which is actually tiny comparing to the whole fracture surface) and crack origin from the lateral surface, fracture under cathodic polarization is suggested to be quasi symmetrical. Therefore the tendency of RA changes due to cold drawing is similar in air and in hydrogenating conditions.

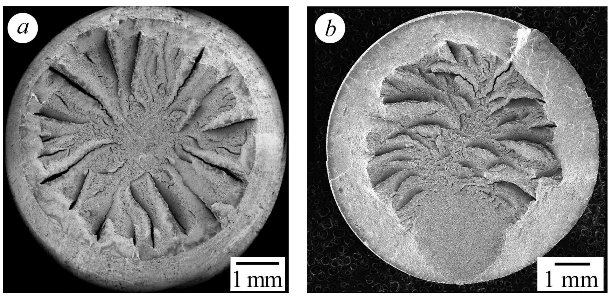

Fig. 3. Microfracture maps of steel E4 after tensile test in air (*a*) and under hydrogenation in the solution containing1 g/l $Ca(OH)_2$ + 0.1 g/l NaCl, pH 12.5 (*b*).

CONCLUSION

Division of the values of reduction in area as a basic plasticity parameter of steel into the components responsible for crack initiation and crack growth allows one to consider the stage of crack initiation and crack propagation separately. It should be noted that a tendency of its changes with strain increment ε are similar for both test conditions, in particular, increase of susceptibility to crack initiation and simultaneous improvement of resistance to crack propagation in heavily drawn steels.

РЕЗЮМЕ. За результатами механічних випроб на повільний розтяг гладких зразків досліджено зміну характеристик пластичності у повітрі та наводнювальному середовищі прутків з перлітної сталі внаслідок холодного волочіння. Сталь високочутлива до водневого окрихчення на усіх етапах обробки. Виявлено невідповідність між змінами відносних звуження та рівномірного видовження. Отримані результати проаналізовано з виокремленням вкладу опору зародженню і поширенню тріщини. Внаслідок холодного волочіння підвищується чутливість до тріщиноутворення, при цьому опір поширенню тріщини дещо зростає.

РЕЗЮМЕ. На основании результатов механических испытаний на медленное растяжение гладких образцов исследовано изменение характеристик пластичности на воздухе и в наводороживающей среде прутков из перлитной стали после холодного волочения. Сталь высокочувствительна к водородному охрупчиванию на всех этапах обработки. Обнаружено несоответствие между относительным сужением и равномерным удлинением. Полученные результаты проанализировали, выделяя отдельно сопротивление зарождению и распространению трещины. Вследствие холодного волочения повышается чувствительность к трещинообразованию, при этом сопротивление распространению трещины повышается.

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