Influence of the inlet die angle on the hydrogen embrittlement of cold drawn prestressing wires

J. Toribio[1,a], M. Lorenzo[1,b], D. Vergara[1,c] and V. Kharin[1,d]

[1] Department of Materials Engineering, University of Salamanca,

E.P.S., Campus Viriato, Avda. Requejo 33, 49022 Zamora (Spain)

[a] toribio@usal.es, [b] mlorenzo@usal.es, [c] dvergara@usal.es, [d] gatogris@usal.es

Keywords: wire drawing, inlet die angle, hydrogen embrittlement, prestressing steel wires.

Abstract. Prestressing steels are highly susceptible to hydrogen embrittlement (HE). Residual stress and strain states, produced after wire drawing, play an essential role in this fracture process because of their influence on hydrogen diffusion and accumulation in prospective fracture places of the material. Therefore, changes in stress and strain fields, due to variations in wire drawing conditions, could modify the life in service of these structural components. This work analyzes, by means of the finite element method (FEM), the effect of the inlet die angle on the obtained residual stress and strain distributions and, therefore, on HE of prestressing steels.

Introduction

Prestressing steel wires, widely used in civil engineering as structural elements in prestressed concrete, are manufactured by drawing. In essence, this process consists of a progressive reduction of the cross sectional area of a previously hot rolled bar when it is forced to pass throughout a rigid die. During the diameter reduction, a non-uniform plastic strain distribution is produced over the cross section of the wire, thereby generating a residual stress state at the end of the process [1,2].

These stress and strain fields are not negligible [1-3], and their effects in fracture processes such as crack initiation and growth could be relevant if tensile states are placed near the surface [4]. In addition to the relevance of residual stress and strain states in the fatigue life of such prestressing steels, those states play a key role in the main fracture mechanism in harsh environments of the steels: hydrogen embrittlement (HE) [1,5,6]. The relevance resides in the strong dependence of the main hydrogen transport mechanism, hydrogen diffusion, on both stress and strain states [5,7]. So, differences observed in residual stress and strain distributions produced by wire drawing could modify fracture and HE behavior. In the particular case of the manufacturing process by cold drawing the die geometry is a key issue in the residual stress and strain generation [4].

This way, the aim of this work is obtaining the residual stress and strain states generated by three different wire drawing processes where a key parameter defining die geometry is varied: the inlet die angle. From these states, it is possible to predict hydrogen diffusion and, finally, to estimate the influence of the inlet die angle on HE of prestressing steels.

Numerical Modelling

Computations were performed by the finite element method (FEM) using a commercial code (MSC.MARC®) by simulating one step cold drawing process considering three different dies with inlet die angles varied within the common range used in the drawing industry (case I: low inlet die angle: $\alpha = 5°$; case II: intermediate inlet die angle: $\alpha = 7°$; and finally case III: high inlet die angle: $\alpha = 9°$). All the processes produce the same wire diameter reduction from an initial diameter of $d_0 = 12$ mm to a final one of $d_1 = 10.80$ mm, as sketched in Fig. 1.

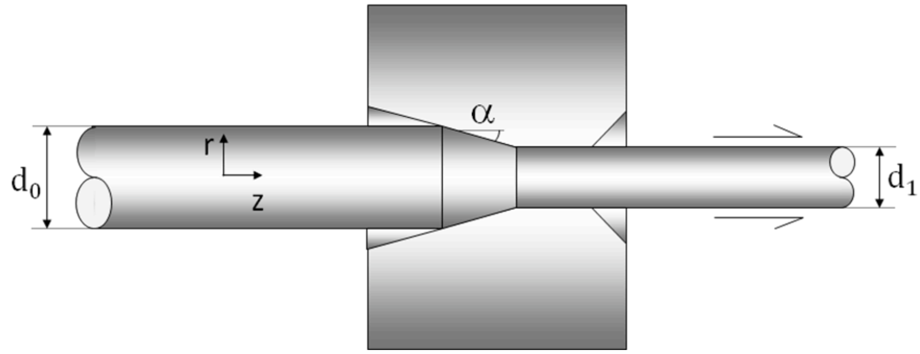


Fig. 1. Scheme of the one step cold drawing process simulated by the FEM.

Analysis was focused on the key mechanical variables governing hydrogen diffusion assisted by both stress and strain: the hydrostatic stress (σ) and the equivalent plastic strain ($\bar{\varepsilon}_{\mathrm{P}}$), cf. [7]:

$$\mathbf{J} = -D(\varepsilon_{\mathrm{P}})\left\{\nabla C - C\left[\frac{v_{\mathrm{H}}}{RT}\nabla\sigma + \frac{\nabla K_{\mathrm{S}\varepsilon}(\varepsilon_{\mathrm{P}})}{K_{\mathrm{S}\varepsilon}(\varepsilon_{\mathrm{P}})}\right]\right\}, \tag{1}$$

C being the concentration, D the hydrogen diffusion coefficient, v_{H} the partial volume of hydrogen, R the universal gas constant and T the absolute temperature. Hydrogen flux depends on the stress and strain state in terms of the hydrostatic stress (σ) and the strain-dependent term of hydrogen solubility ($K_{\mathrm{s}\varepsilon}$) which can be linearly dependent of equivalent plastic strain ($\bar{\varepsilon}_{\mathrm{P}}$), as follows:

$$K_{\mathrm{S}\varepsilon}(\bar{\varepsilon}_{\mathrm{P}}) = 1 + 4\bar{\varepsilon}_{\mathrm{P}}. \tag{2}$$

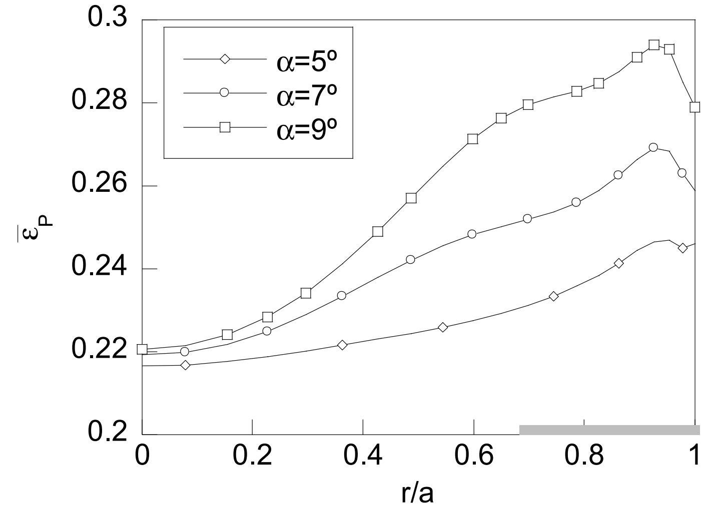
The amount of hydrogen at wire surface can be obtained from the steady state solution of the differential equation of hydrogen diffusion that takes the following form for long times of exposure to harsh environment:

$$C_{\mathrm{eq}} = C_0 K_{\mathrm{S}\varepsilon}(\varepsilon_{\mathrm{P}})\exp\left[\frac{v_{\mathrm{H}}}{RT}\nabla\sigma\right]. \tag{3}$$

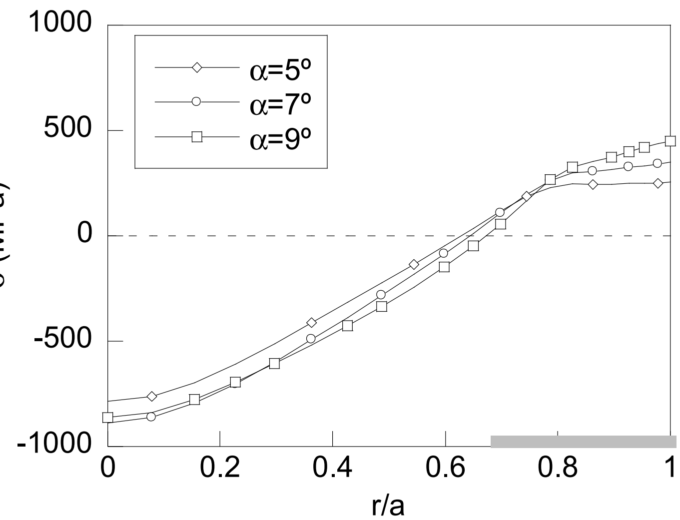
Results

Fig. 2 and Fig. 3 show respectively the equivalent plastic strain and the hydrostatic stress distribution throughout the dimensionless radial coordinate (r/a), a being the outer wire radius, for the three cold drawing processes analysed.

As it can be noticed in Fig. 2 equivalent plastic strain is quite sensible to variations in inlet die angle. This influence is observed throughout the whole wire radius with the exception of wire centre where the differences are remarkable lower. According to these results the wire drawing with lower inlet die angle generates a lower and more uniform equivalent plastic strain distribution along the wire cross section. As this parameter increases, the equivalent plastic distribution becomes higher and less uniform. This effect is particularly noticeable near to wire surface ($0.65 < r/a < 1$) where the higher differences were achieved and a significant increment (about 90%) of the gradient of equivalent plastic strain is observed ($0.93 < r/a < 1$). This is highly relevant for the hydrogen diffusion process because this gradient, which is directly related with the gradient of hydrogen solubility, acts as a driving force for hydrogen diffusion according to Eq. 1.



(a)



(b)

Fig. 2. (a) Equivalent plastic strain and (b) hydrostatic stress distribution throughout the dimensionless wire radius in the three cold drawing processes analysed in this paper.

With regard to the hydrostatic stress distribution the same trend is observed in the three wire drawing processes studied (Fig. 2b). Tensile stress states are placed at surface and compressive at inner points close to wire centre. As observed in plastic strain distribution, the lower and more uniform distribution is obtained in the wires drawn with the lower inlet die angle, and, as this parameter increases, the stress distribution becomes higher and less uniform. Main differences are observed in a zone placed close to wire surface ($0.8 < r/a < 1$) precisely at the zone where the maximum plastic strain values were obtained (Fig. 2a). For the lower value of inlet die angle the hydrostatic stress gradient is almost null and progressively decreases as the inlet die angle increases. In addition, the hydrostatic stresses at surface increases with inlet die angle.

Discussion

From obtained results a qualitative estimation of the HE susceptibility of the wires could be carried out. Cold drawing effects on residual stress and plastic strain distributions are strongly concentrated

at wire surface surroundings (0.7 < r/a < 1) with minor perturbations at inner points. On one hand, the increment of both the gradient of plastic strain from the surface and the maximum value of such a plastic strain with inlet die angle implies respectively an increment of one of the driving forces for diffusion and an increment of hydrogen solubility. On the other hand, the inlet die angle produces two competing effects on residual hydrostatic stress distributions: firstly, the reduction of the gradient of hydrostatic stress from the surface implies a reduction of other of the driving forces for diffusion (and thus slower diffusion could be expected) and, secondly, the increment of the residual hydrostatic stress at the surface implies an increment of the amount of hydrogen at surface.
A simple estimation of the hydrogen distribution for long time diffusion (ensuring that the steady state is reached) is obtained from Eq. 3. The increment of both stress and plastic strains at surface implies the same effect: an increment of the hydrogen concentration at wire skin. Consequently, in those wires there is more potentially diffusible hydrogen towards the inner points. In addition, the amount of hydrogen over the high stressed and strained zone increases with the inlet die angle (grey zone in Fig. 2a and 2b) and, therefore, the potential damage caused by hydrogen at microstructural level could be more intense in those wires drawn with high inlet die angles. According to these results, the higher the inlet die angle used in wire drawing, the higher the increment of the susceptibility to HE in the cold drawn wires.

Conclusions

Obtained results show that inlet die angle is a key parameter in wire drawing process. The relevance of such a parameter resides in the following fact: a low variation in the inlet die angle causes significant changes in residual stress and strain states, and consequently in hydrogen accumulation within the material that could produce hydrogen embrittlement (HE) of the cold drawn wires.
Main differences produced by different inlet die angles during cold drawing in residual stress and strain states are localized in a zone placed near the wire surface obeying the following rule: the lower the inlet die angle the lower the residual stress and strain at the surface with a more uniform distributions of both residual stress and plastic strain throughout the wire radius.
According to previous reasoning, it can be concluded that the optimum condition for cold drawing is obtained with small inlet die angles because under these conditions the residual stress and strain state is lower and more uniformly distributed. So, the HE susceptibility of the wires would be lower too, thereby producing a longer life of prestressing steel in hydrogenating environments.

Acknowledgements

The authors acknowledge the financial support provided by the following Spanish Institutions: MCYT (Grant MAT2002-01831), MEC (Grant BIA2005-08965), MCINN (Grants BIA2008-06810 and BIA2011-27870) and JCYL (Grants SA067A05, SA111A07 and SA039A08).

References

[1] J. Toribio, V. Kharin, M. Lorenzo and D. Vergara: Corros. Sci. Vol. 53 (2011), p. 3346.
[2] J.M. Atienza, J. Ruiz-Hervias, M.L. Martinez-Perez, F.J. Mompean, M., Garcia-Hernandez and M. Elices: Scripta Mater. Vol. 52 (2005), p. 1223.
[3] H. Överstam: Mater. Processing Tech. Vol. 171 (2004), p.446.
[4] K. Katagiri, T. Sato, K. Kasaba, S. Sasaki and H. Tashiro: Fatigue Fract. Eng. Mater. Struct. Vol. 22 (1999), p. 753.
[5] J. Toribio and M. Elices: Int. J. Solids Struct. Vol. 28-6 (1991), p. 791.
[6] J.P. Hirth: Metal. Trans. Vol. 11A (1980), p. 861.
[7] J. Toribio, V. Kharin, D. Vergara and M. Lorenzo: Adv. Mater. Res. Vol. 138 (2010), p. 117.