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# On the use of varying die angle for improving the resistance to hydrogen embrittlement of cold drawn prestressing steel wires

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ABSTRACT

Residual stresses produced by cold drawing are an undesirable effect of the non-uniform plastic strain distribution generated during the conforming process used for obtaining prestressing steel wires. Among the diverse parameters of the process influencing the residual stress generation, one of the most relevant is the geometry of the drawing die and, in particular, the inlet die angle. Wires drawn with die angles as low as possible will exhibit a lower and more homogeneous plastic strain state and, therefore, a smaller and more uniform residual stress state. Thus the hydrogen embrittlement (HE) susceptibility of such wires is also lower, thereby enlarging the life in service of these components. In this paper an innovative design of the drawing die is proposed using two consecutive angles (i.e., varying die angle) for reducing the residual stress and strain state in the cold drawn wires and, consequently, for improving the resistance to HE of prestressing steel wires.



## 1. Introduction

Prestressing steel wires, widely used in civil engineering as components of prestressed concrete structures, are obtained by means of a conforming process called cold drawing [1] in which a progressive diameter reduction is undergone by the wire. During this process a non-homogeneous distribution of plastic strain is generated, thereby causing the appearance of residual stresses [2,3]. Such states are heavily influenced by die geometry [4–7] and the strain history undergone during the multi-pass drawing [8,9].

One of the key parameters affecting the generation of such states is the inlet die angle [10,11]. This way, wire drawings which use low values of such a parameter generate plastic strain and stress states less intense and more homogenously distributed through the wire radius. These changes produced in the residual stress and strain states improve the mechanical behavior of these components against fatigue or fracture in harsh environments, such as hydrogen embrittlement (HE), a damage process to which prestressing steels are particularly susceptible [12–14].

This paper analyzes the residual stress and strain states generated at the end of an innovative wire drawing process in which the dies were designed considering *varying die angle* (in the form of two consecutive die angles) and their implications on the HE of the cold drawn wires. To do so, diverse numerical simulations of wire drawing including conventional and modified dies were carried out by the finite element (FE) method covering diverse cases in which the die angles were varied. Thus, the improvement of the stress and strain state can be quantitatively estimated comparing those states produced by proposed die geometries with those obtained using a conventional wire drawing method where the whole process is

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performed under a *constant die angle*. From these results a calculation of the hydrogen amount for long times of exposure to hydrogenating environments can be made, thus allowing the determination of the optimal case for a better assessment of the structural integrity of these components.

## 2. Numerical modeling

To obtain the residual stress and plastic strain distributions in the wire, a simulation was performed by FE of diverse wire drawing processes by considering two different types of wire drawing dies: on one hand the conventional ones (Fig. 1) with *constant inlet die angle* where a constant wire diameter reduction is considered; on the other hand the proposed innovative die geometry (Fig. 2), in which the wire diameter decrement is applied during two consecutive reductions with *varying* (*decreasing*) *inlet die angle*, and thus proposed drawing die is more compact (smaller size).

### 2.1. Conventional wire drawing (constant die angle)

A conventional drawing die is mainly composed by two zones (Fig. 1). Firstly, the wire diameter is progressively decreased during the reduction zone (A–B in Fig. 1). This zone is defined by the inlet die angle ($\alpha$). Secondly, after this zone, the bearing zone (B–C in Fig. 1) allows the wire adaptation to the new dimensions. This zone is defined by means of the bearing length ($l_z$).

In this paper the first drawing pass (initial step) was chosen from *real* multi-pass wire drawing chain provided by a wire drawing company, where an initial hot rolled bar of diameter $d_0$ = 12 mm becomes a drawn wire of $d_1$ = 10.8 mm. It means a net diameter reduction of 10%. For quantitative estimation of the improvement of the proposed drawing dies, three different conventional wire drawing process were considered in which the main variable, the inlet die angle, is varied according to previous analyses [10,11]: (i) case 1 with high inlet die angle $\alpha = 9°$, (ii) case 2 with medium inlet die angle $\alpha = 7°$, (iii) case 3 with low inlet die angle $\alpha = 5°$, the optimum die geometry from the fracture mechanics viewpoint when conventional wire drawing with constant inlet die angle is used, as explained in a previous work [11].

### 2.2. Innovative wire drawing (varying die angle)

For defining the geometry of the modified drawing die shown in Fig. 2 where the reduction zone is divided into two consecutive reductions (AA′ and A′B in Fig. 2), an additional parameter is needed: the *secondary die angle* ($\alpha_2$) since a secondary reduction is considered after the main diameter decrement defined by the *primary die angle* ($\alpha_1$). Afterwards, the same bearing length was considered for all the cases of study assuming that no changes were produced when the bearing length is equal or higher than a characteristic value defined in a previous work [11].

To determine the potential improvements in the stress and strain state using this innovative drawing procedure, two die geometries with varying angle were analyzed considering different values for the primary die angle and the same secondary die angle ($\alpha_2 = 5°$) as in the case of the optimum conventional wire drawing process (using a single die with low angle) proposed in [11]. Thus, the cases analyzed with an innovative die geometry are the following: (i) case 1* with high primary die

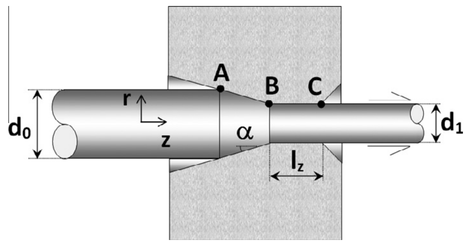


**Fig. 1.** Conventional wire drawing (constant die angle): single diameter reduction during drawing.

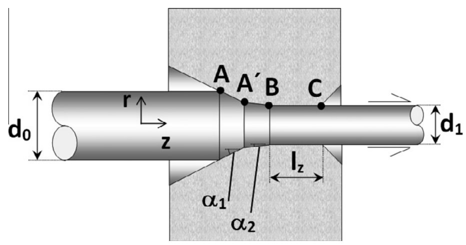


**Fig. 2.** Innovative wire drawing (varying die angle): two consecutive diameter reductions during drawing.