Engineering Failure Analysis 36 (2014) 215–225

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Influence of the die geometry on the hydrogen embrittlement susceptibility of cold drawn wires

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ARTICLE INFO

Article history:
Received 12 September 2013
Accepted 9 October 2013
Available online 18 October 2013

Keywords:
Wire drawing
Die geometry
Residual stress–strain fields
Hydrogen diffusion
Hydrogen embrittlement

ABSTRACT

Residual stress and strain states produced by wire drawing play an essential role in the main cause of failure of cold drawn wires: hydrogen embrittlement (HE), because of the influence of such fields on hydrogen diffusion within the material lattice. Therefore, variations on stress and strain fields, due to changes in the wire drawing process conditions, could modify the service life of these structural components. In this work the influence on HE of two parameters of the wire drawing process (the inlet die angle and the die bearing length) are analyzed by means of diverse numerical simulations by the finite element method (FEM). According to the obtained results, the effects of residual stress and strain fields produced by wire drawing on HE are less dangerous when the inlet die angle decreases or when the bearing length exceeds a characteristic value (wire radius), with a remarkable reduction of the driving forces for hydrogen diffusion. Consequently, wires drawn under such conditions (lower inlet die angle and longer bearing length) will exhibit a lower susceptibility to HE, thereby increasing their resistance to engineering failure.
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1. Introduction

Prestressing steel wires, widely used as structural components in civil engineering, are obtained by a conforming process called cold drawing. During this conforming process, a progressive reduction of the wire diameter is carried out forcing the wire to pass through a die, thereby causing the appearance of a non-uniform distribution of plastic strain over the cross sectional area of the wire [1,2]. As a result, the wire undergoes important changes at the microstructural level that modify macroscale mechanical properties in the form, e.g., of a remarkable increment of the yield strength or an increment of the fracture toughness [3,4]. Nevertheless, plastic strains also generate an undesirable non-negligible residual stress state [1,2,5–7] that, acting together with plastic strains, could reduce the structural integrity of these structural components during their service life in the presence of harsh environments [1,2] causing catastrophic in-service fracture [8,9]. Furthermore, the residual stress state of tensile nature at surface could enhance fatigue crack initiation and growth leading to premature failure in service [10,11]. For these reasons, several studies were focused on the determination of the stress states generated during the conforming process by means of laboratory techniques such as X-ray or neutron diffraction [6,12,13]. However, actually none of these experimental procedures provides information about plastic strain distributions (another key issue in hydrogen diffusion and thus in HE susceptibility). Therefore, numerical simulation of the conforming process by cold drawing is a very interesting tool to achieve a complete knowledge of both residual stress and plastic strains [1,2,7].

In addition to the relevance of residual stress and strain states on the fatigue life of prestressing steels, such states play a key role in the main mechanism of wire fracture in harsh environments: hydrogen embrittlement (HE) [1,2,14–17] causing a

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1350-6307/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfailanal.2013.10.010

serious reduction of the structural integrity of the prestressing steel wire [8,9]. According to diverse studies [15–17], hydrogen diffusion within material lattice, the main stage of the HE process, is highly dependent on the stress and strain state into the material. Hence, it seems to be interesting to act as much as possible on such states in order to improve the prestressing steels wires performance in harsh environments by modifying those process parameters affecting the generation of plastic strains and, therefore, of residual stresses. Diverse studies [7,18–23] found out that such states are affected by die geometry. Detailed analyses of the improvement obtained when wire drawing is performed with new die designs were carried out [19,23]. These designs optimize the drawing process by modifying residual stress and strain states at the end of the process. However, most of them are focused on analyzing only changes on residual stresses, and no information about values of plastic strains for HE analysis is given. So, from existing data it seems to be difficult to analyze the advantages of modifying the stress and strain state in the wires, the main cause of failure of prestressing steels in harsh environments [8,9].

In order to fill this gap, the aim of this study is (i) to quantitatively determine the stress and strain states generated by diverse cold drawing processes where both parameters defining die geometry: the inlet die angle and the bearing length, were varied and, from those, (ii) to estimate the HE susceptibility of such wires considering the hydrogen distributions obtained from the numerical simulation of hydrogen diffusion assisted by stresses and strains. This way, the most adequate conditions to perform wire drawing process could be estimated leading to an improvement of the wire performance during its service life under hydrogen environment.

2. Numerical modeling

In order to determine the influence of the die geometry on the HE of prestressing steels the study was divided into two uncoupled analyses by means of (i) numerical simulations by the finite element method (FEM) of the wire drawing process using a commercial code (MSC.Marc) for quantitatively determining the residual stresses and strains after each one of the wire drawing process considered, and (ii) numerical analysis of the hydrogen diffusion process assisted by stresses and strains using the previous simulations results as input data in an *ad hoc* non-commercial code (MathCAD) developed by the authors for obtaining the hydrogen distributions through the wire section.

The contact zone between the wire and die can be defined just by two parameters (Fig. 1) representing the two stages that wires undergo during the conforming process: firstly, the *reduction zone* (A and B in Fig. 1) where the wire diameter is progressively reduced, defined by the inlet die angle (α), and secondly, the *bearing zone* (B and C in Fig. 1) whose aim is enhancing the adaptation of the wire to the new dimensions which can be defined by the die bearing length (l_z).

2.1. Wire drawing

Six different simulations of the first step of a commercial wire drawing process were carried out. In this drawing stage the cross sectional area of the wire is reduced from an initial diameter d_0 = 12 mm to a final one d_1 = 10.8 mm. For the analysis of the inlet die angle, three cases of study were considered corresponding to three drawing process where the diameter reduction is performed by using three different inlet die angles: (i) large inlet die angle $\alpha = 9°$, (ii) medium inlet die angle $\alpha = 7°$, and (iii) a small inlet die angle $\alpha = 5°$ considering for all cases a commonly used value for the die bearing length ($l_z = d_0/2$).

With regard to the bearing length, another three process were simulated varying such a parameter according to the characteristic value ($l_z = d_0/2$) suggested by reference [24] as follows: (i) a case where the bearing length is lower than the characteristic value ($l_z = d_0/4$) (ii) a second case where the length is equal to the characteristic value ($l_z = d_0/2$) and, finally, (iii) a case where the length is higher than the characteristic bearing length ($l_z = d_0$) considering for all cases a commonly used inlet die angle ($\alpha = 7°$).

Axisymmetric formulation was used due to the cylindrical symmetry of both the wire and the die. Elastoplastic large deformations with updated lagrangian formulation were used. Several meshes were used until required mesh convergence was achieved. The constitutive model used was elastoplastic solid with von Mises yield surface, associated flow rule, and isotropic strain-hardening according to [2] for the eutectoid steel with the following mechanical properties: Young modulus, E = 196 GPa and yield strength σ_Y = 696 MPa. Considering the final aim of the die (causing the reduction of the wire cross section without significant elastic strains or fracture) ceramic materials such as tungsten carbide are fixable for this component. Consequently, the die was modeled as a perfectly rigid material with a Young modulus, E = 600 GPa.

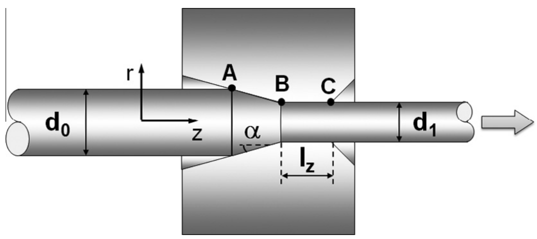

Fig. 1. Scheme and parameters used to define a commonly used wire drawing die.

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