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Mechanical integrity of corrosion product films on rotating cylinder specimens

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ABSTRACT

Rotating cylinder (RC) technique is widely used for flow corrosion testing. However, this test configuration has limitations. Particularly, integrity of corrosion products films formed on the RC surface can be affected. The objective of this work is to show how intense the stresses in corrosion product films can be at high rotation speeds. In such cases, failure of the films is possible due to inertial forces rather than other factors, such as flow, leading to erroneous results. Consequently, theoretical calculation of stresses in films has been performed and a case of corrosion product film failure assessed using a fracture mechanics approach.

1. Introduction

The rotating cylinder (RC) technique has been widely used in corrosion laboratory testing to determine the effect of flow velocity on corrosion rates [1–8]. The obtained information can be used to predict the corrosion behavior of the internal walls of pipes in industrial applications. This is usually achieved by using characteristic flow-related parameters such as the mass transfer coefficient, for which formulations for RC configuration are available elsewhere [5,6]. However, this test configuration is not exempt from complications. Particularly, the rotation-induced inertial forces acting on the whole volume of the RC can play an important role on the integrity of solid corrosion products or deposits that may form on the RC surface.

The objective of this paper is to show that the stresses in RC corrosion product films can be significant, particularly when high rotation speeds are employed. Under these conditions unnatural failure of corrosion product films may be possible due to inertial forces rather than other well-known factors under study, such as flow, which leads to erroneous conclusions.

Regarding this matter, a theoretical approach to the calculation of the stress field of corrosion product films is introduced. Moreover, an experimental case of film failure is assessed using available fracture mechanics knowledge. The results indicate that under certain experimental conditions the use of the RC technique can provoke spontaneous fracture of the corrosion product film, which is undesired in the corrosion test.

1.1. Stresses in corrosion product films attached on the cylindrical external surface of a RC

Uniform corrosion product layers attached on a metallic surface can be modeled as thin films. If a uniform isotropic elastic film of thickness h is completely adhered on the cylindrical external surface of a RC (Fig. 1), it can be presumed that the attached surface of the film will share the same displacement field as the substrate surface (attachment boundary condition). This is expressed as the equality of the strains of the film and the strains of the substrate surface in the tangential (t) and the axial (z) directions:

$$\varepsilon_{tf} = \varepsilon_{ts} \quad (1)$$

$$\varepsilon_{zf} = \varepsilon_{zs} \quad (2)$$

The subscripts f and s indicate whether the strain corresponds to the film or the substrate surface, respectively.

As the film is considered to be very thin, its radial stress component can be neglected ($\sigma_{rf} \sim 0$). Moreover, the constraint that the adhered film could cause on the substrate is also ignored; this means that if the substrate is loaded in some way it will respond as if nothing is on its surface.

If the cylinder length is larger than its diameter and the cylinder is unloaded in the axial direction, the axial strain of the substrate

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Nomenclature list

a	half of the length of a preexisting characteristic defect in the corrosion product film
α_f	thermal expansion coefficient of the film
α_s	thermal expansion coefficient of the substrate
α, β	Dundurs parameters
ΔT	temperature variation
E_f	Young's modulus of the film
E_o	Young's modulus of the pore-free material of the film
E_s	Young's modulus of the substrate
ε_{tf}	tangential strain in the film
ε_{ts}	tangential strain in the substrate
ε_{zf}	axial strain in the film
ε_{zs}	axial strain in the substrate
f	friction factor
$f(a/l,\upsilon_f)$	dimensionless function of a/l and υ_f estimated by means of numerical methods
$g(\alpha,\beta)$	dimensionless function dependent on the Dundurs parameters
h	film thickness
K_C	critical stress intensity factor
K_{IC}	critical mode I stress intensity factor
K_I	mode I stress intensity factor
K_o	bulk modulus of the pore-free material of the film
l	reference length
υ_f	Poisson's ratio of the film
υ_o	Poisson's ratio of the pore-free material of the film
υ_s	Poisson's ratio of the substrate
P	porosity of the film material
R_1	inner radius of the RC
R_2	outer radius of the RC
Re	Reynolds number
ρ_s	density of the RC material
ρ_{fl}	density of the fluid around the RC
σ_{ij}	stress tensor
σ_{rf}	radial normal stress component in the film
σ_{rs}	radial normal stress component in the substrate
σ_{rr}	radial normal stress component in the corrosion product film of $FeCO_3$
σ_{rt}	shear stress component in the corrosion product film of $FeCO_3$ (acting in tangential direction)
σ_{tf}	tangential normal stress component in the film
σ_{ts}	tangential normal stress component in the substrate
σ_{tt}	tangential normal stress component in the corrosion product film of $FeCO_3$
σ_{zf}	axial normal stress component in the film
σ_{zs}	axial normal stress component in the substrate
σ_{zz}	axial normal stress component in the corrosion product film of $FeCO_3$
σ_t	thermal stress in the film
τ_w	wall shear stress
U	velocity at the surface of the RC
μ_{fl}	dynamic viscosity of the fluid around the RC
ω	rotation speed

can be ignored ($\varepsilon_{zs} = 0$ and $\sigma_{zs} \neq 0$). The radial stress component of the surface substrate (σ_{rs}) is considered as zero.

Using Hooke's law (strain–stress relationship) to relate the strains in the film and in the substrate with their respective stresses, the Eqs. (1) and (2) can be written as:

$$\frac{\sigma_{ts} - \upsilon_s\sigma_{zs}}{E_s} = \frac{\sigma_{tf} - \upsilon_f\sigma_{zf}}{E_f} \tag{3}$$

$$\frac{\sigma_{zs} - \upsilon_s\sigma_{ts}}{E_s} = \frac{\sigma_{zf} - \upsilon_f\sigma_{tf}}{E_f} = 0 \tag{4}$$

where E_f and E_s are Young's moduli of the film and the substrate, respectively; υ_f and υ_s are Poisson's ratios of the film and the substrate, respectively; σ_{rf}, σ_{tf} and σ_{zf} are the radial, tangential and axial normal stresses in the film, respectively; σ_{rs}, σ_{ts} and σ_{zs} are the radial, tangential and axial normal stresses in the substrate surface, respectively.

Combining Eqs. (3) and (4), the tangential and the axial stresses in the film can be expressed as a function of the surface tangential stress of the substrate:

$$\sigma_{tf} = \sigma_{ts}\frac{(1-\upsilon_s^2)E_f}{(1-\upsilon_f^2)E_s} \tag{5}$$

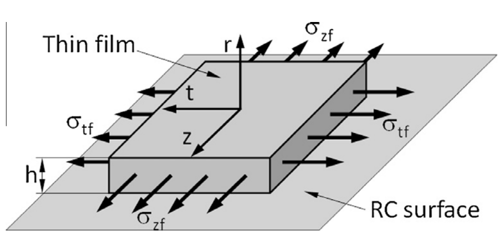

Fig. 1. Schematic of a portion of a uniform thin film attached on the RC surface.

$$\sigma_{zf} = \sigma_{ts}\frac{\upsilon_f(1-\upsilon_s^2)E_f}{(1-\upsilon_f^2)E_s} \tag{6}$$

From Eqs. (5) and (6) the stresses in the film have a linear dependence on the tangential stress of the substrate surface (σ_{ts}). The main factor that controls the stress transferred from the substrate to the film is the quotient between Young's moduli of the film and the substrate materials (E_f/E_s).

1.1.1. Rotation-induced stresses

Rotating solid bodies develop internal stresses in order to equilibrate the volume forces produced by the resulting accelerations. In the case of a RC apparatus, the working piece or electrode can be modeled as a rotating hollow cylinder made of an isotropic elastic material.

If the RC rotates at constant speed (ω) around its symmetry axis (named here z), the developed internal stresses will be: radial stress (σ_r), tangential stress (σ_t), and axial stress (σ_z). These stresses are present through the section of the RC and vary with the radius [9].

Consequently, If a thin film is adhered or deposited on the cylindrical external surface of a stationary RC and subsequently the RC is rotated at a constant speed (ω), it will experience normal stresses in the tangential and the axial directions due to the strains in the substrate. According to Eqs. (5) and (6), the tangential stress at the RC surface will be needed to calculate the stresses in the adhered film. From integrating differential equations (Hooke's law and force balance) and applying boundary conditions ($\sigma_{rs}(R_1) = \sigma_{rs}(R_2) = 0$; surfaces are unloaded in the radial direction at R_1 and R_2, internal and external radii of the hollow cylinder, respectively), the tangential stress at the RC surface results [9]:

$$\sigma_{ts} = \frac{\rho_s\omega^2}{4(1-\upsilon_s)}[(3-2\upsilon_s)R_1^2 + (1-2\upsilon_s)R_2^2] \tag{7}$$