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Numerical study on the evaluation of thermal and mechanical stresses during the welding of coated pipelines

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ABSTRACT

The safety of pipeline networks is a priority, especially when these networks get older. The protection against corrosion is realized by coupling a passive coating with an active cathodic protection. It is well known that the presence of internal stresses in organic coatings is a current phenomenon which can result in the loss of adhesion. This phenomenon is critical for the durability of pipelines. The welding process and its consequences on the stress generated in the pipeline are investigated in this paper. Using a finite element approach, the welding process is simulated, and the thermal and mechanical evolutions are analyzed. From these results, the stress is essentially concentrated in the steel cylinder. Indeed, the cutback realized on the coating allow its protection during the welding.

1. Introduction

Pipelines networks have been highly developed all over the world, both for onshore and offshore transportation. The lifetime control of these installations is essential to guarantee a continuous production. As example, for underground steel pipeline, the lifetime expected exceeds fifty years [1]. In a recent study about Alberta network [2], 70% of the pipeline rupture have been identified to a slow degradation under service of the pipe while only 30% can be affected to an exceptional event or due to a third party [2–4]. This report shows that corrosion is one of the major cause of the pipeline failure as show on Fig. 1.

To secure pipeline integrity and preserve their durability, conventional active cathodic protection [5–8] is often coupled to passive protection based on anticorrosion coatings [9–11]. The coating is a chemical, mechanical and electrical barrier between the steel cylinder and the environment. The cathodic protection consists in decreasing the potential of the steel up to obtain an electronegative value to prevent the corrosion phenomena [12].

For underground pipeline, two different coatings are generally used. The first, dedicated to the US market, is based on a monolayer system of fusion bonded epoxy (Fig. 2a). The second one is based on three layers polyolefin coatings. It is composed by a fusion bonded epoxy, a modified polyolefin adhesive and a thick polyolefin topcoat as shown in Fig. 2b. These two coating protection have been highly used for over 20 years and have some advantages and disadvantages [13].

Recently, many feedbacks all over the world have been reported about a massive disbonding of the coating in the case of the three-layers coating in service only for a few years [14–16]. The disbonding is observed at the steel/coating interface without damage on the coating top surface. Moreover, no corrosion has been observed on the steel pipeline under these disbonding areas. Roche et al. [16] have concluded about a degradation of the Steel/FBE interface due to the water diffusion throughout the coating. This disbonding has never been observed on the monolayer coating which is subjected to similar water uptake. Legghe et al. [17], by a finite element approach, have shown that the stress levels in the three-layers coating are 4 times higher than in the monolayer coating. For the three-layers coating, Legghe et al. [17] have shown that the higher stress is at the FBE/PE interface. Moreover, Tchoquessi [18] has highlighted that significant inhomogeneous stresses are present in the coating in service. The presence of internal stresses in coating [19–22] and their consequences [23–25] are well described in the literature. Applied to pipeline coatings, stresses can be generated during: the process, the welding and in service.

The process of pipeline coating has been well studied in the literature. Chang et al. [26–28] have studied the stress generated during the process by using a finite element and analytical models. The authors show that the coating will compress the steel cylinder and will be in opposition to the disbonding phenomena. The 2D models used by the authors give only the radial stresses in the pipe. Legghe et al. [29] have developed a more realistic numerical model where the properties of the materials depend on temperature. The authors conclude about an overestimation of the stresses in the coating due to the conservative law applied in the model. Introduction of viscoelasticity behaviors for the polymeric materials allows more realistic stress values [30–32]. A stress

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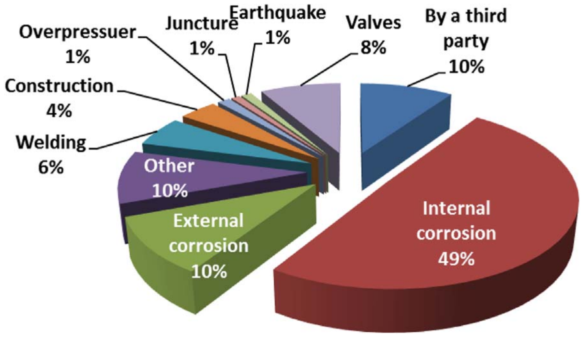

Fig. 1. Pipeline failures by cause between 1990 and 2012 on Alberta pipeline network [2].

at the interface steel/epoxy around 17 MPa is calculated with the numerical models. This value is lower than the stress at rupture upper than 30 MPa measured experimentally [18,33]. These results show significant stresses in the coating due to the process but they can not explain the massive disbonding observed in service.

The aim of this paper is to complete the previous works by the study of the welding step. During the welding, the temperature applied on the steel cylinder may affect and damage the interface steel/coating. A numerical model is developed to estimate the stress generated in the pipeline during the welding.

2. Materials and methods

Pipeline network is built by the orbital arc-welding method. The welding speed is usually between 80 and 150 mmmin^{-1}. Many authors have proposed analytical or numerical models able to estimate the thermal affected area during the welding. Harinadh et al. [34], applying a finite element approach, have obtained three different temperature distribution characteristic of the three regions of fusion areas, heat affected areas and base plate. The temperatures calculated vary from 30 °C in the base plate and up to 2300 °C in the fusion zone. Alves do Carmo et al. [35] have developed finite element models and compared the numerical results to experimental measurements. A maximum value of temperature around 2000 °C is calculated from the models. By means of the modeling of the arc-welding method, Sun et al. [36] have calculated a maximum value around 1800 °C in the fusion areas. This maximal value has been chosen as temperature of welding applied in the numerical model (most unfavourable case).

The numerical models developed should take into account the thermal properties evolution versus temperature in order to give realistic results. So, materials properties were described up to 2300 °C (maximum value from the literature).

2.1. Steel properties vs temperature

Steel properties versus temperature have been estimated from room temperature and from the Eurocode 3.

The standard value for the density of structural steel proposed by

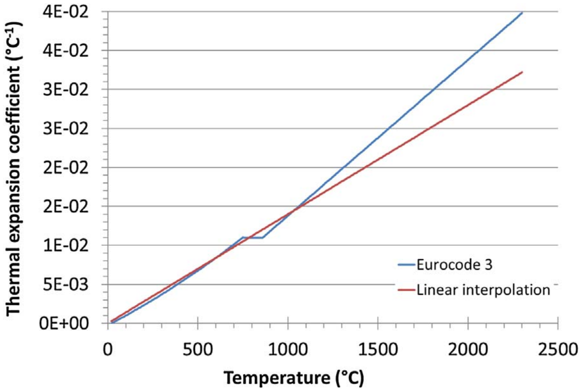

Fig. 3. Thermal expansion coefficient vs temperature for steel [37].

Eurocode 3 is 7850 kgm^{-3}. It is generally accepted that density is constant whatever the temperature is. So, a constant value will be used in the numerical model.

At room temperature, the values of coefficient of thermal expansion (CTE) classically admitted in the literature are between 10.10^{-6} to 20.10^{-6} °C^{-1}. The temperature (T) dependence of the CTE for steel is obtained from Eqs. (1)–(3) [37].

$$\alpha = (-2.416x10^{-4}) + (-1.2x10^{-5})T + (-0.4x10^{-8})T^2 \quad \text{for} \quad T \leq 750\,^{\circ}\mathrm{C} \tag{1}$$

$$\alpha = 0.011 \text{ for } T < 750\,^{\circ}\mathrm{C} \leq 860\,^{\circ}\mathrm{C} \tag{2}$$

$$\alpha = -0.062 + (2x10^{-5})T \quad \text{for} \quad T > 860\,^{\circ}\mathrm{C} \tag{3}$$

In simple calculations, the CTE of steel may be assumed to have a linear evolution described by Eq. (4):

$$\alpha = 1.4x10^{-5}\Delta T \tag{4}$$

Fig. 3 compares the two evolutions of CTE *vs* temperature. So, in the rest of this work, a linear interpolation will be introduced to describe the thermal expansion coefficient of steel in all numerical models.

In literature, the thermal conductivity coefficient of the steel is around 20–60 W m^{-1} K^{-1} at room temperature. The evolution of the thermal conductivity coefficient (λ) with temperature (T) can be described by Eqs. (5) and (6) [37]:

$$\lambda = 54 - \frac{T}{20} \quad \text{for } 20\,^{\circ}\mathrm{C} < T \leq 800^{\circ}\mathrm{C} \tag{5}$$

$$\lambda = 27.3 \text{ for } T > 800\,^{\circ}\mathrm{C} \tag{6}$$

The curve described in Fig. 4 will be introduced in numerical models for thermal conductivity coefficient of steel vs temperature evolution.

A relation between the specific heat (Cp) and temperature (T) is also proposed in the Eurocode 3. Eqs. (7)–(10) describe the variation of Cp *vs* the temperature within different ranges of temperature. The

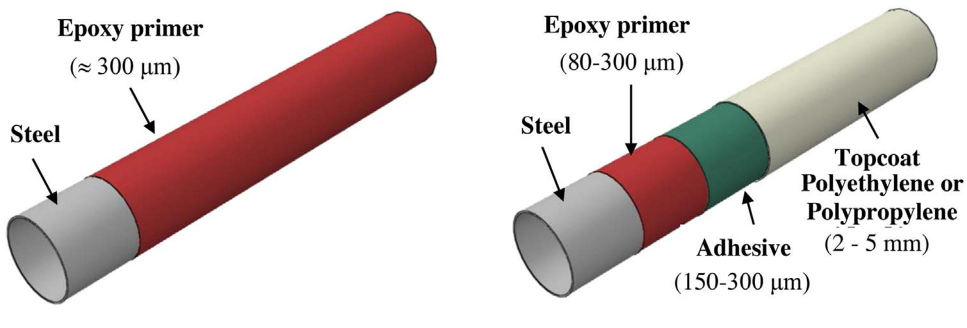

Fig. 2. Schematic representation of the monolayer and the three layers coatings on pipelines.