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Numerical modeling of stresses relaxation phenomena in the complex assembly steel pipe/three layers polyethylene coating

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ABSTRACT

Three-layer coatings are highly used to achieve long-term protection against corrosion. The coating is composed by a thick polyolefin topcoat, a modified polyolefin adhesive and a fusion bonded epoxy. Many observations suggest that significant internal stresses are present in the coating. Moreover, internal stresses in organic coatings can generate loss of adhesion and decrease the lifetime of the assembly. The aim of the study is to simulate relaxation phenomena during storage phase and to quantify residual stresses, in order to appreciate if they are critical for adhesion and sustainability of the assembly. During this stage, polyethylene or epoxy are able to relax all or a part of internal stresses as it necessarily occurs with any polymer.

1. Introduction

External passive three layers polyolefin coatings are frequently associated to an active cathodic protection to ensure integrity of buried steel pipelines [1–3]. Premature degradations of pipelines network could be a critical issue which could generate serious financial and environmental consequences [4–7]. Three layers polyolefin coatings are thus designed to ensure a fine protection against corrosion and extend pipelines lifetime. Adhesion and anticorrosion properties of fusion bonded epoxy are combined to mechanical protection provided by thick polyolefin topcoat. The intermediate layer consists of a copolymer adhesive layer which allows binding highly apolar polyolefin topcoat to highly polar epoxy primer (Fig. 1).

This coating system has very good adhesion, excellent barrier properties, low sensitivity to cathodic disbondment and excellent mechanical properties [8–10]. Yet, few cases of spontaneous coating disbondments at steel/epoxy interface have been observed on several kilometers of buried pipelines dedicated to oil transportation [11,12]. The expertise of these cases of premature disbondments does not always allow to identify the precise origin of these phenomena, and the development of internal stresses inside the assembly during coating's implementation appeared as one of the most plausible causes. Indeed, the epoxy primer is electrostatically sprayed onto the steel tube preheated at 200 °C. The adhesive and the topcoat are then successively extruded over the hot primer and the whole system is rapidly submitted to a water quenching at 20 °C [14].

As often reported, internal stresses are generated by thermal expansion coefficients mismatch between the steel's tube and the materials constituting the coating [13–18]. Finite element modeling appeared as an essential tool to quantify these stresses. So far, none of the experimental methods described in literature does allow the measurement of residual stresses in a coated steel pipe because of its complex geometry [19–23]. Given that the real mechanical behaviour for epoxy or polyethylene relies on visco-elasto-plastic laws, it has been demonstrated that numerical calculations based on non linear thermo-viscoelastic constitutive law are the most relevant thermo-mechanical models to quantify stress levels generated by water quenching of a hot three layers polyethylene coating [24–27]. It has thus been computed that soon after water quenching of a standard coated pipe (steel internal diameter: 602.7 mm/steel thickness: 7.3 μm/FBE thickness: 150 μm/PE adhesive thickness: 300 μm/PE topcoat thickness: 3.1 mm), a maximal shear stress level of 22 MPa was reached in the adhesive layer, near fusion bonded epoxy/adhesive interface, at the edges of the coated pipe. Far from assembly's edges, interfacial stresses levels were respectively about 2 MPa and 4 MPa at

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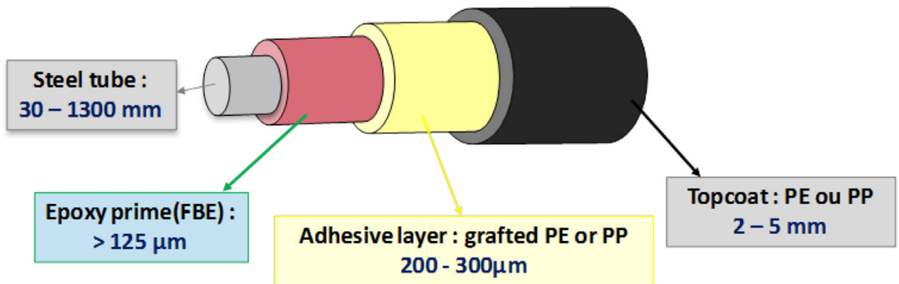

Fig. 1. Three layers polyolefin coatings (PE: polyethylene/PP: polypropylene).

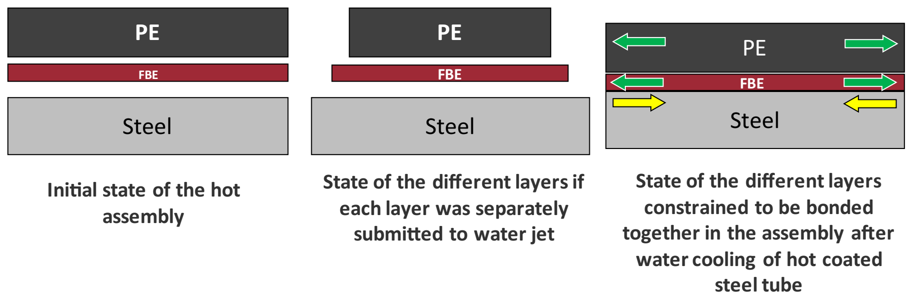

Fig. 2. Schematic explanation of stresses generation in three layers polyethylene steel pipe due to thermal expansion coefficients mismatch (α_{steel} = 12E−6 °C^{-1}; α_{FBE} = 24E−6 °C^{-1}; α_{PE} = 175E−6 °C^{-1}).

steel/epoxy interface and at epoxy/polyethylene adhesive interface.

Here, the aim of the study is to simulate relaxation phenomena during storage phase and to quantify residual stresses, in order to appreciate if they are critical for adhesion and sustainability of the assembly. Indeed, soon after coating's implementation, coated tubes are stored at ambient air before being transported to pipelines constructions sites. This storage period varies typically between six months and one year, but may be extended over longer periods. During this stage, polyethylene or epoxy are able to relax all or a part of internal stresses as it usually occurs with any viscoelastic polymer.

2. Experimental parameters determination

Stress relaxation describes how polymers relieve stress under constant strain. Because they are viscoelastic, polymers behave in a non Hookean way. This nonlinearity is described by both stress relaxation and a phenomenon known as creep, which describes how polymers strain evolves under constant stress. It has been chosen to perform relaxation tests on epoxy and polyethylene raw materials, because the three layers polyethylene coating is actually kept at constant strain on steel tube after cooling of the assembly as schematically explained by Fig. 2.

During a quasi-static relaxation test, an initial strain $\varepsilon 0$ is applied at the initial time t_0 (Fig. 3). This ïnstantaneousštrain induces an initial stress $\sigma 0$. The initial strain is kept constant (Fig. 3a) while the stress decreases with time (Fig. 3b) due to creep and stress relaxation. Under constant strain, the material gradually returns to a more stable state and the mean stress takes some time to reach its final value.

Uniaxial tensile tests were carried out on a tensile testing machine MTS Adamel Lhomargy DY25 at room temperature (20 °C). The tests were performed with three dumbbell specimens according to ISO 527-3:1995 standard geometries specifications. The reference length is 30 mm, the width is around 4 mm and the thicknesses are 2.5 and 0.5 mm for PE and epoxy respectively.

Epoxy films were implemented in the laboratory. The epoxy powder was directly sprayed on a steel plate thanks to an electrostatic gun. The steel plate was first recovered with a release agent and preheated at 220 °C as in the industrial process [24]. The PE test bars were cut from a coating stemming from an industrial application. Strain of 2% and 4% were respectively kept constant for epoxy and polyethylene samples and the evolution of stress over time was recorded (Fig. 4)

With ABAQUS^{TM} software, materials viscoelasticity can be modeled either by introducing normalized parameters stemming from relaxation tests, or by using the generalized Maxwell model, described by a series of exponentials named Prony series. The generalized Maxwell model is the most general form of the linear model for viscoelasticity. This model considers that relaxation in a polymer cannot be described by a single characteristic time, but by a distribution of times associated to the distribution of molecular chain length segments with different molecular mobilities. It is then assumed that shorter ones contribute less than longer ones, which induces the time distribution. The generalized Maxwell shows this by having as many spring–dashpot Maxwell elements as necessary to represent accurately the distribution (Fig. 5). Each spring is characterized by an elastic modulus and each dashpot by a viscosity η_i. Here, g_i is a dimensionless elastic modulus, normalized by the instantaneous elastic modulus g_0. g_i and η_i are used to define the relaxation time $\tau_i = \eta_i/g_i$.

The case of small deformation has been considered. Indeed after water quenching of the assembly, it has been pointed out that deformations levels were low [26]. The maximum level of distortion in the radial direction was of the order of 4%, while it was below 0.1% in the longitudinal direction. Eq. (1) can thus depict Prony series associated to dimensionless relaxation modules $g_R(t)$.

$$g_R(t) = 1 - \sum_{i=1}^{N} g_i \left(1 - e^{\frac{-t}{\tau_i}}\right) \quad (1)$$

ABAQUS^{TM} software was then used to determine the parameters of Prony series using a non linear least square method to fit properly experimental relaxation curves of epoxy and polyethylene samples obtained from one-dimensional relaxation test (Fig. 4).