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Numerical modelling of pipe internal stresses induced during the coating process – Influence of pipe geometric characteristics on stress state

M.R. Tchoquessi Diodjo [a,*], L. Belec [a], E. Aragon [a], F.X. Perrin [a], M. Bonnaudet [b], L. Lanarde [b], M. Meyer [b], Y. Joliff [a,*]

[a] Laboratory MAPIEM, Université du Sud Toulon Var, Avenue Georges Pompidou, BP 56, 83957 La Garde, France
[b] GDF Suez, DRI-CRIGEN, Pôle Mécanique, Matériaux, Intégrité des structures, 361 Avenue du président Wilson, BP 33, 93211 Saint-Denis, La Plaine, France

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A B S T R A C T

The presence of internal stresses in organic coatings is a well-known phenomenon that can generate loss of adhesion. In the case of external coatings used to achieve long-term protection against corrosion, three-layer coatings are widely employed. They are composed by a thick polyolefin topcoat, a modified polyolefin adhesive and a fusion bonded epoxy. Several observations corroborate the existence of internal stresses in the coating. Furthermore, pipes of various diameters and thicknesses are found on the market depending on the in-service technical requirements. The aim of this finite element study is to show the influence of the steel pipe geometry on the internal stresses calculated in three-layer systems after the cooling process. Then the study is focused on a standard coated pipe in order to determine the optimal thicknesses of the different layers. For these purposes, a nonlinear thermo-mechanical approach by finite element modelling with Abaqus™ is used.

1. Introduction

External corrosion of underground or submerged pipelines is a critical issue that can generate serious financial and environmental consequences [1,2]. To preserve the structure integrity, a dual protection based on an active cathodic protection and a passive anti-corrosion coating is usually implemented [3–6]. The efficiency of this concurrent system of protection is dependent on the adhesive bond strength between steel and the coating. Moreover this bond must remain strong enough over pipeline lifetime [7]. The coating must fulfil specific conditions such as good mechanical strength, good disbonding resistance and good ageing resistance.

Nowadays, three layers polyolefin coating composed by a fusion bonded epoxy, a modified polyolefin adhesive and a thick polyolefin topcoat, are the most widely used systems in Europe (Fig. 1).

During construction and in operation, pipelines are submitted to several stresses, which can damage the coating. Impacts can occur during pipeline laying over the ditch or during back filling operations. Besides, the soil stresses in operation pipelines [8]. The polyethylene topcoat thus acts as a mechanical protection, while the adhesive layer ensures an optimal link between the highly apolar polyethylene topcoat and the highly polar epoxy primer. Epoxy networks are often involved in the bonding of organic coatings for their good mechanical properties [9]. In addition, these thermosets present low shrinkage after curing, good adhesion to a wide range of substrates, and good resistance to disbondment from steel substrates under cathodic polarization [10,11], which may explain why it is currently one of the most used primers by oil and gas companies all around the world [12]. In the particular case of three layers polyolefin coating, the epoxy primer function is to protect the metal against corrosion and to improve its resistance to cathodic delamination.

In two specific cases, loss of adhesion has been observed on pipes [13,14], which could result from internal stresses generated during the cooling stage of the coating application. Indeed, the epoxy primer is electrostatically sprayed onto the pipe heated by induction at about 200 °C. The adhesive and the topcoat are then successively extruded over the hot primer and the whole system is rapidly cooled down by means of a water quenching phase (Fig. 2) [15].

Residual stresses are generated at the interfaces due to thermal expansion coefficients mismatch between steel and the different layers of the coating, as often reported [16–20]. Indeed, in this range of temperature, the polyethylene topcoat evolves from a viscous fluid to the solid state through a partial crystallization [21]. This crystallization concerns a layer of several millimetres thick and induces a high cooling down of the topcoat in comparison to steel. The development of internal stresses might also occur in coating layers by changes in relative humidity of the environment

* Corresponding authors. Tel.: +33 4 94 14 26 28 (M.R. Tchoquessi Diodjo), +33 4 94 14 29 74 (Y. Joliff).
E-mail addresses: tchoques@univ-tln.fr (M.R. Tchoquessi Diodjo), joliff@univ-tln.fr (Y. Joliff).

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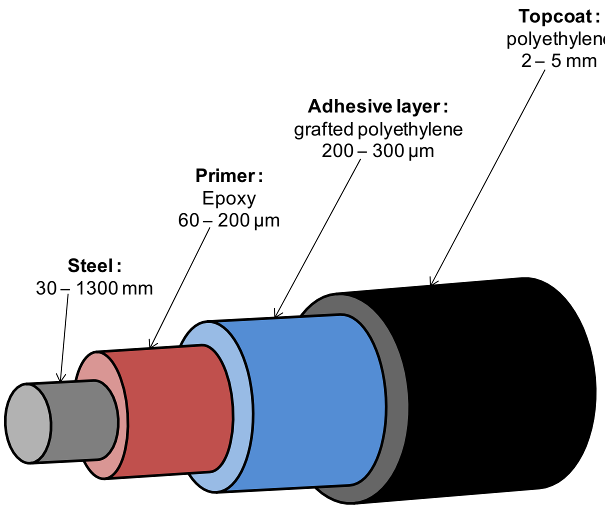

Fig. 1. Three layers polymer coating.

or by the crosslinking of the epoxy primer leading to the formation of a three-dimensional network onto steel [22]. As a matter of fact, soon after the coated pipe water quenching and before the cutbacks preparation, a coating withdrawal going up to 3 cm is observed at the ends of a 20 m long pipe. Premature damages in the polyolefin adhesive layer or at steel/epoxy interface, in form of disbondment of the coating have also been observed at pipes' ends during extended outdoor storage, prior to pipeline construction, especially when cutbacks are not properly protected against direct water access to the epoxy layer, by means of a water proof varnish for example. Moreover, it has been observed that disbondment at epoxy/steel interface could occur onto in-service pipelines without apparent external coating defects, after a service period shorter than the expected lifetime of the pipeline. Owing to variations of thermal, mechanical and geometrical properties of the system, as well as to variations of coating application process, it has been suspected that interfacial stresses developed during pipeline processing may be close to mechanical strength of the interfaces, leading to these premature coating damages.

Some experimental methods allow measuring internal stresses in different materials, particularly in coatings [23–28], yet depending on the geometry of the test samples, these methods are difficult to implement. Deflection tests on samples in form of beams, developed by Corcoran are the most common method [23]. In our case, it appears impossible to realize such a three layers sample representative of a real system; consequently a realistic internal stress state cannot be reproduced for residual stresses' measurement purpose. Many authors have proposed analytical models to calculate internal stresses in multi-layers systems [29–31]. Chang et al. focused on stresses generated in three-layer systems [32,33]. Their analytical calculation is based on revolution symmetry with a section analysis which takes into account only radial stresses. However, the disbonding observed from the edges of the pipes seems to point out the occurrence of a longitudinal stress effect. Thermal contraction induces radial stresses which only constricts the coating onto the steel substrate and is likely to limit coating disbondment [34]. Longitudinal shear stresses will be taken into account in this work.

The goal of this study is to analyze and quantify the distribution of residual stresses inside the coated pipes after completion of the coating application process, as a possible critical factor of the premature damages phenomena observed in three-layer systems, and specifically to discriminate the role of some parameters such as the geometrical characteristics of the pipe and its coating on the level and distribution of these residual stresses. First, internal stress levels developed after the water quenching period are estimated as a function of the steel pipe and its coating system geometries. Then the study focuses on standard pipes' dimensions and coatings' constitutions, in order to determine the optimal thicknesses of the different coating's layers for minimizing the residual stresses left at interfaces. For these purposes, finite element modelling using ABAQUS™ software is used. The calculation is based on nonlinear thermo-mechanical constitutive laws for the coating and steel materials, and most numerical input data related to the material properties result from experimental measurements in the temperature range of the coating application process.

2. Experimental parameters determination

To predict the materials behaviour during the pipe's quenching period, several material properties are required as input data in the numerical model [35,36]. These data can derived from literature, yet this information is often incomplete and never corresponds exactly to our materials characteristics, especially in terms of temperature dependence. So, when it was possible, most of these parameters were measured through dedicated experimental tests performed on specific specimens. The source of all input data is summarized in Table 1.

The specific heat (C_p) is measured at 2 K/min after calibration on a sapphire reference with a Modulated Differential Scanning Calorimeter, Q100 from TA Instruments (Fig. 3).

Young's modules are obtained from thermo-mechanical measurements in dynamic mode on a DMA 2980 from TA Instruments (Fig. 4). For this purpose, a tension film clamp is used (Fig. 5). Samples are 3 cm long, 1 cm wide and about 200 µm thick. A preload of 1 N magnitude is applied, in order to keep the film under tension during the test. DMA is used at 1 Hz in linear viscoelastic range.

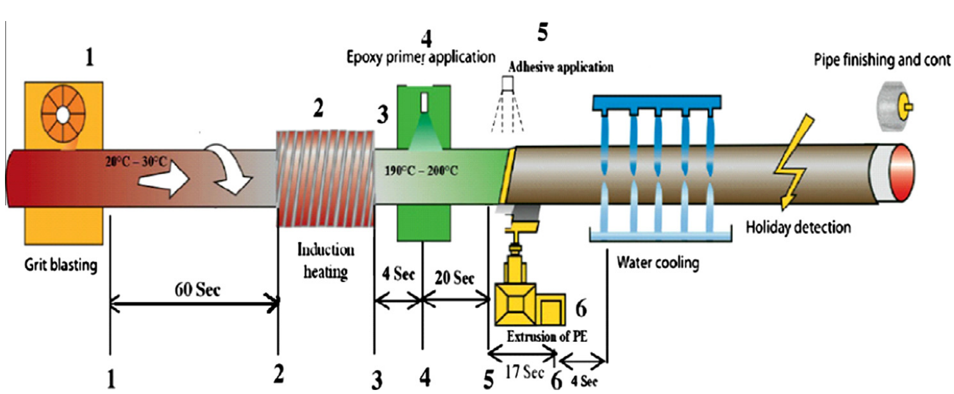

Fig. 2. Application process of three-layer pipe coatings by lateral extrusion [14].