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Stress evolution in multilayer polymer coating under thermal and pressure loading applied to the pipeline structure

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32 **Nomenclature**

33

DMA	Dynamic Mechanical Analysis	α	Coefficient of thermal expansion
		C_p	Specific heat
FC	Safety coefficient	C_1	Coefficient of viscoelasticity
FBE	Fusion Bonded Epoxy	C_2	Coefficient of viscoelasticity
		ϕ	Diameter
MOP	Maximum Operating Pressure	E	Young's modulus
		e	Thickness
PE	Polyethylene	g_i	Relaxation modulus
PPP	Polypropylene	J	Compliance
		λ	Thermal conductivity
R_e	Yield strength	ν	Poisson coefficient
		σ	Stress
WLF	Williams, Landel and Ferry law	ρ	Density
		T	Temperature
		t	Time
		τ_i	Relaxation time

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35 **1. Introduction**

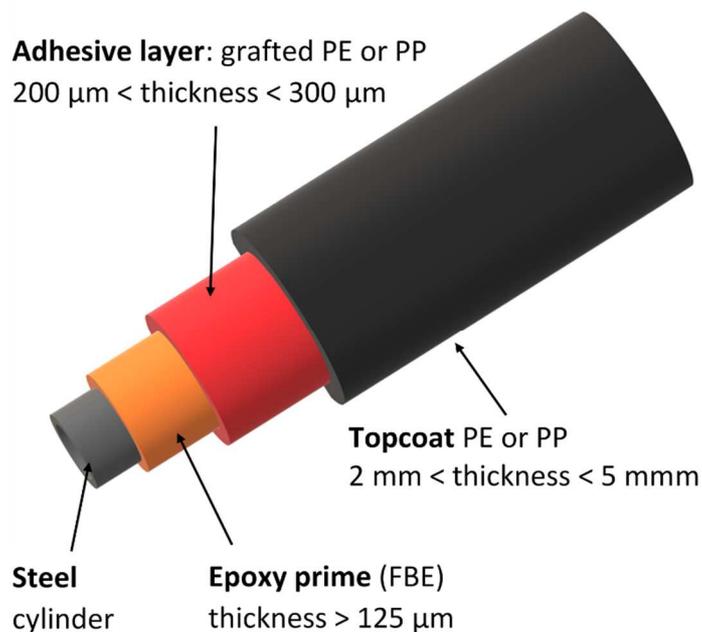
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37 Thousands of kilometres of steel pipes are available to transport natural gas under pressure.
38 Gas network consists of sections of pipes and related structures that fulfil specific functions in
39 order to transport the fluids in optimal conditions. The injection stations constitute the entry
40 points of the transport network. The compressor stations are evenly distributed along the
41 transport networks to maintain the pressure and velocity of the gas in the pipelines. The
42 delivery stations ensure the delivery of natural gas to manufacturers or downstream
43 distribution networks. Delivery stations deliver natural gas to industrial companies or
44 downstream distribution networks. These stations provide the functions of expansion,
45 reheating, filtering or measuring gas.

46 There are many studies in the literature that investigate the durability of these systems in
47 service [1, 2, 3, 4, 5, 6]. Most of these studies deal with the problems of corrosion [7, 8, 9, 10]
48 or mechanical cracks but only a few are dedicated to the durability of the coating system. To
49 improve the lifetime of the steel cylinder against the corrosion, a passive anti-corrosion
50 coating system (Figure 1) is generally used in addition to cathodic protection [11, 12, 13, 14,

51 15].

52 Two types of coatings are mainly used. The first one, based on a single-layer system, consists
53 in coating the steel cylinder with about 600 μm thick of epoxy layer (Fusion Bonded Epoxy
54 FBE). This type of pipeline is mainly dedicated to American market. The second type of
55 pipeline coating, used for the European market, is based on a three-layers system that
56 associates a primer epoxy layer (Fusion Bonded Epoxy FBE), an adhesive polyethylene layer
57 (PE Adhesive) and a polyethylene topcoat (PE Topcoat) [16]. The role of the FBE layer is to
58 ensure an excellent adhesion between the steel substrate and the PE layer. This coating also
59 allows good barrier properties. The PE Adhesive layer ensures an efficient link between FBE
60 layer and PE Topcoat. The PE Topcoat allows a good chemical and mechanical resistances.
61 The pipeline is manufactured by a semi-continuous process during which the steel cylinder is
62 heated up to 200°C. The FBE layer is applied by spraying a powder at the surface of the
63 heated steel cylinder. The PE Adhesive and PE Topcoat layers are then extruded on the latter.
64 The pipeline then undergoes a rapid cooling in order to solidify the coating before storing at
65 ambient air.



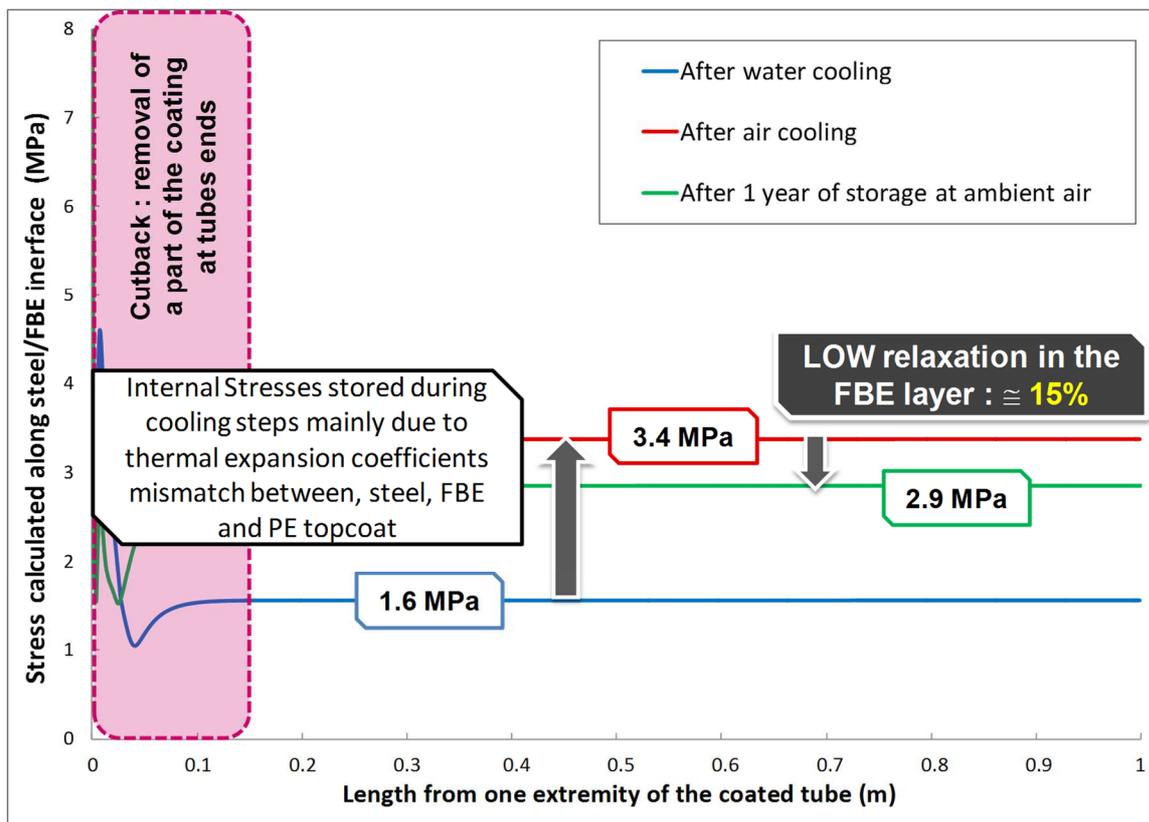
66

67 **Figure 1: Thickness of three layers polyolefin coatings (FBE: Fusion Bonded Epoxy /PE: polyethylene / PP: polypropylene)**

68 A number of negative feedbacks have been reported about a massive disbonding of the
69 coating in the case of the three-layer coating in service since a few years [17, 18, 19]. This
70 disbonding has been observed at the steel/coating interface without damage to the coating top
71 surface. Moreover, no corrosion has been observed on the steel pipeline under these
72 disbonding areas. Roche et al. [18] have concluded about a degradation of the Steel/FBE
73 interface due to the water diffusion throughout the coating. If the diffusion of water molecules
74 in the coating is a credible assumption, the rare cases of similar damage on new pipelines can
75 hardly be explained. Moreover, to our knowledge, there has been no such case of reported
76 damage on pipelines coated with monolayer epoxy systems while these systems are also
77 sensitive to water diffusion. Legghe et al. [20], with a numerical approach, have estimated the
78 internal stresses levels generated during the processing of monolayer and three-layer coated
79 pipelines. Considering an elastic behaviour (more unfavourable case – without dissipation) in
80 a first approximation, the authors obtain a large gap (x4) between stress levels in both
81 systems. All these observations suggest that the stresses at the steel/coating interface
82 generated during the coating pipeline process might cause the disbonding of the coating.

83 Some authors [21, 22, 23, 24] have estimated the stress in multi-layered coating. In the case of
84 the pipeline coating [25, 26, 27, 28, 29, 30, 31, 32], this stress is usually due to the mismatch
85 of thermal expansion coefficients of steel and polymer coating. Indeed, a longitudinal
86 contraction can be observed after the pipeline coating process [18]. A similar result has been
87 obtained by numerical simulation of the process with around 12 mm of coating contraction for
88 a pipeline with a length of 20 m [33]. In a previous work [34], it has been shown that far from
89 pipeline extremities, interfacial stress levels are less than 5 MPa at steel/epoxy interface and
90 less than 16 MPa at epoxy/polyethylene interface. Moreover, in another study [35], the impact
91 of the pipeline geometrical characteristics on the stress level was evaluated. It has been
92 demonstrated that radial contraction increases linearly with increase of pipe diameter, which

93 is beneficial for adhesion of the coating. Moreover, whatever the size of the pipe, a stress
 94 around 5 - 7 MPa is calculated at the steel/epoxy interface. All these results converge to the
 95 existence of stresses at the interfaces. During the storage, the stress level will decrease due to
 96 the relaxation of the coating (Figure 2). After one year of storage, the residual stress at the
 97 steel/FBE interface (3MPa) is higher than the residual stress at the FBE/PE interface (2 MPa)
 98 [16].



99

100 Figure 2: Evolution of the Tresca criteria along steel/FBE interface after the different types of cooling process and after 1
 101 year of storage at ambient air [16]

102 If a residual stress is well identified at the steel/coating interface, its intensity cannot explain
 103 the damage observed on the pipeline. A possible cause of this disbonding could come from
 104 the coupling between this internal stress due to the process and the stress generated in
 105 operation (temperature and pressure). So, this paper proposes to continue this investigation on
 106 the quantification of the stresses in coated pipeline in service conditions by a finite element
 107 approach. In service, pipelines are buried in soils and transport more or less hot fluids under

108 pressure. Fraldi et al. [36] show that the mismatch of Young's moduli and Poisson ratios of a
109 polymer multilayers promotes its delamination. So, the influence of internal pressure and
110 service temperatures on the stresses in the three-layer coating will be investigated. Numerical
111 models are compared to experimental data and industrial feedback.

112

113 2. Materials and method

114

115 The metal structure is designed to withstand the internal and external pressure acting on the
116 structure. The thickness, diameter and grade of steel are determined according to the MOP
117 criteria (Maximum Operating Pressure). This criteria is calculated from Equation 1 [37].

$$MOP = FC \times R_e \times \frac{2 \cdot e_{Steel}}{\phi_{Steel}} \quad \text{Equation 1}$$

118 where R_e is the yield strength of the grade of steel used, e_{Steel} and ϕ_{Steel} represent respectively
119 the thickness and the nominal pipe (i.e. inside diameter) of the steel cylinder and FC is a
120 safety coefficient which depends on class location of the pipe. For example, a site identified
121 as category 1 corresponds to a cross-country gas pipeline (no sensitive equipment at
122 proximity).

123 In this work, the geometry of one of the most common pipelines of the GRTgaz transport
124 network is chosen. It is a steel tube with a wall thickness of 7.3 mm and an inside diameter of
125 602.7 mm. GDF SUEZ company recommends the use of steel with a yield strength of 383
126 MPa. These pipes are intended for operation at 72% of the yield strength of steel for class 1
127 location where the safety factor is equal to 0.72. In this case, according to Equation 1, the
128 maximum operating pressure is equal to 6.6 MPa.

129 Furthermore, natural gas is transported through gas pipelines at temperatures between -20 °C
130 and +60 °C. The gas temperature and soil temperature will be considered for the
131 determination of interfacial stresses. Three cases will be considered: two extremes cases

132 where gas temperature is either -20 °C or +60 °C and soil temperature is +20 °C, and a most
133 common case where gas and soil are at the same temperature of +15 °C (Table 1).

134 **Table 1: Three thermal parameters considered**

	Case (a)	Case (b)	Case (c)
$T_{\text{soil}} \text{ (}^\circ\text{C)}$	20	15	20
$T_{\text{gas}} \text{ (}^\circ\text{C)}$	-20	15	60

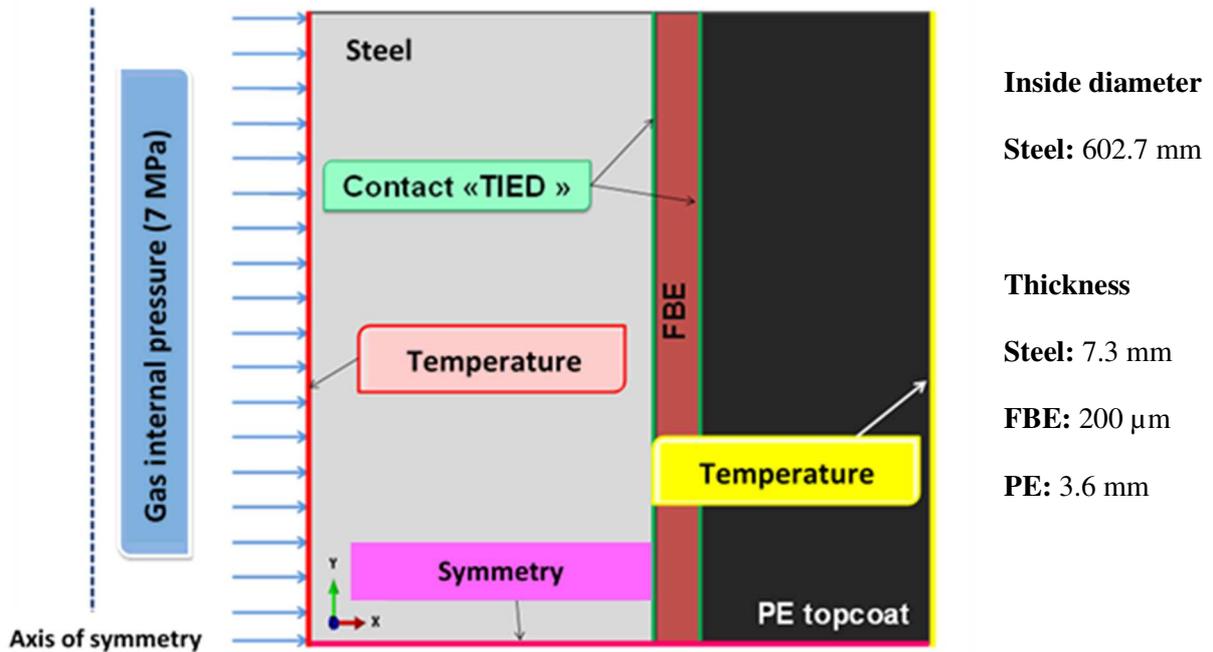
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136 **2.1. Numerical model (Finite element method - FEM)**

137

138 A commercial Finite Element Analysis software, AbaqusTM [38], is used in this work. The
139 properties of the PE Adhesive and PE Topcoat layers being similar, the thickness of the
140 adhesive layer will be added to the thickness of the PE Topcoat in the models. The numerical
141 model is based on an axisymmetric representation to describe the pipeline structure. It has
142 been previously shown that only 1 meter of pipeline length can be considered for the
143 numerical models [33]. A coupled thermomechanical calculation is realized to describe the
144 problem. **A study of the convergences of the various mesh elements (quadrangle ou**
145 **triangular) was made in advance of this work [39].** Each part has been meshed from
146 **quadrilateral** elements with a linear interpolation (**4 nodes**) and a reduction of integration
147 points (**element type CAX4RT**). The mesh is built using the "Structured" technique. The
148 boundary conditions applied on the pipeline are detailed in Figure 3. An internal pressure
149 equal to 6.6 MPa (MOP value from Equation 1) is applied to the inner surface of the pipe
150 **(blue arrows in Figure 3)**. This study considers a buried pipeline. External pressure is
151 neglected in this work. Three temperature conditions are imposed on the internal surface of
152 the metal cylinder in contact with the gas **(red line in Figure 3)** and on the top surface coating
153 in contact with the soil **(yellow line in Figure 3)**. **A perfect contact (Tied – green lines in**
154 **Figure 3) is assumed between the different layers of coating and the steel pipe. No debonding**

155 can appear during the simulation for any interface. A total transmission of the thermal and the
156 mechanical properties from one material to another one is allowed.



157 Figure 3: Loading and boundary conditions applied on the pipeline

158

159 Considering the previous results [16, 34, 35], the model based on the thermo-viscoelastic
160 behaviour is the most performing and it has been chosen for this study.

161 With ABAQUSTM software, materials viscoelasticity can be modelled either by introducing
162 normalized parameters stemming from relaxation tests, or by using the generalized Maxwell
163 model described by a series of exponentials named Prony series. The generalized Maxwell
164 model is the most general form of the linear model for viscoelasticity. This model considers
165 that relaxation in a polymer cannot be described by a single characteristic time, but by a
166 distribution of times associated to the distribution of molecular chain length segments with
167 different molecular mobilities. It is then assumed that shorter ones contribute less than longer
168 ones, which induces the time distribution. The generalized Maxwell shows this by having as
169 many spring-dashpot Maxwell elements as necessary to represent accurately the distribution.
170 Each spring is characterized by an elastic modulus and each dashpot by a viscosity η_i . Here,

171 g_i is a dimensionless elastic modulus, normalized by the instantaneous elastic modulus g_0 . g_i
 172 and η_i are used to define the relaxation time $\tau_i = \eta_i/g_i$.
 173 ABAQUSTM software was then used to determine the parameters of Prony series using a non
 174 linear least square method to fit properly experimental relaxation curves [16].
 175 Williams, Landel and Ferry proposed an empirical equation (WLF law) which gives an
 176 equivalence between time and temperature (Equation 1). T represents the temperature, T_{ref} is
 177 the reference temperature (glass transition temperature or operating temperature for example).
 178 C_1 and C_2 are empirical constants.

$$179 \log(a_T) = \frac{-C_1(T-T_{ref})}{C_2+(T-T_{ref})} \quad (1)$$

180 The principle of time-temperature equivalence states that the passage from T_{ref} to T amounts
 181 to multiplying the time scale by a thermal shift factor $a_{T \rightarrow T_{ref}}$ which depends only on T and
 182 T_{ref} . Thus, there is a relation between compliance at the reference temperature and compliance
 183 at the temperature considered: $J(t, T_{ref}) = J(t \times a_{T \rightarrow T_{ref}}, T)$. By a suitable transformation of
 184 the abscissa scale, for each temperature, we can obtain the superposition of the curves.
 185 Constants C_1 and C_2 are adjusted so that Equation 1 is verified.
 186 Input data for simulation are specified in Table 2, Figure 4, Figure 5, Table 3 and Table 4.
 187 These values come from experimental measurements or from the literature [40].

188 **Table 2: Thermal and mechanical parameters used in the models**
 189

Materials	λ (W.m ⁻¹ .K ⁻¹)	ρ (kg.m ⁻³)	E (GPa)	ν	α (K ⁻¹)	Cp (J.kg ⁻¹ .K ⁻¹)
Steel	21 ^(a)	7800 ^(a)	210 ^(a)	0.30 ^(a)	12x10 ⁻⁶ ^(a)	650 ^(a)
FBE	0.35 ^(a)	1400 ^(a)	f(T) ^(b)	0.33 ^(a)	24x10 ⁻⁶ ^(a)	f(T) ^(c)
PE	0.63 ^(a)	955 ^(a)	f(T) ^(b)	0.42 ^(a)	175x10 ⁻⁶ ^(a)	f(T) ^(c)

190 with λ thermal conductivity, ρ density, E Young's modulus, ν Poisson coefficient, α Coefficient of thermal expansion and Cp
 191 specific heat (a) from literature [40], (b) by dynamic mechanical analysis tests, (c) by modulated differential scanning
 192 calorimetry tests
 193
 194

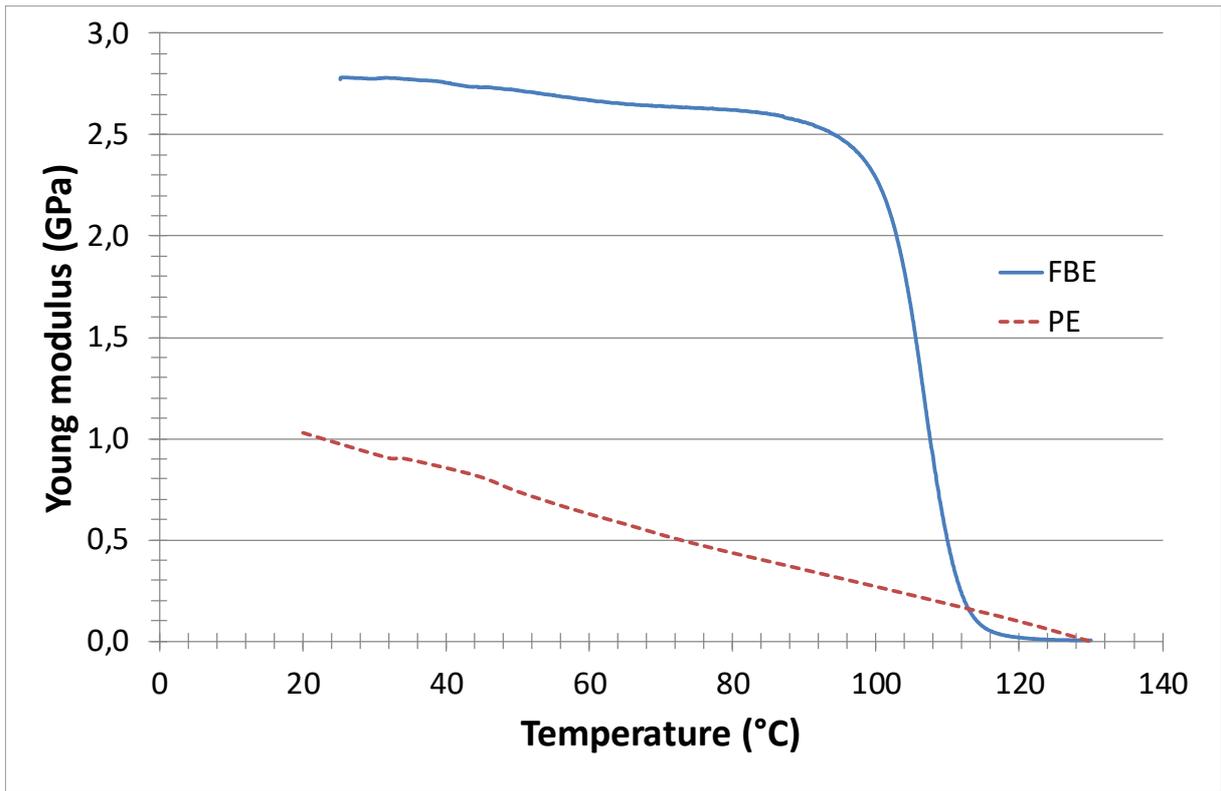


Figure 4: Young modulus as a function of temperature for polyethylene and epoxy (DMA at 1 Hz in shear mode in linear viscoelastic range)

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196
197

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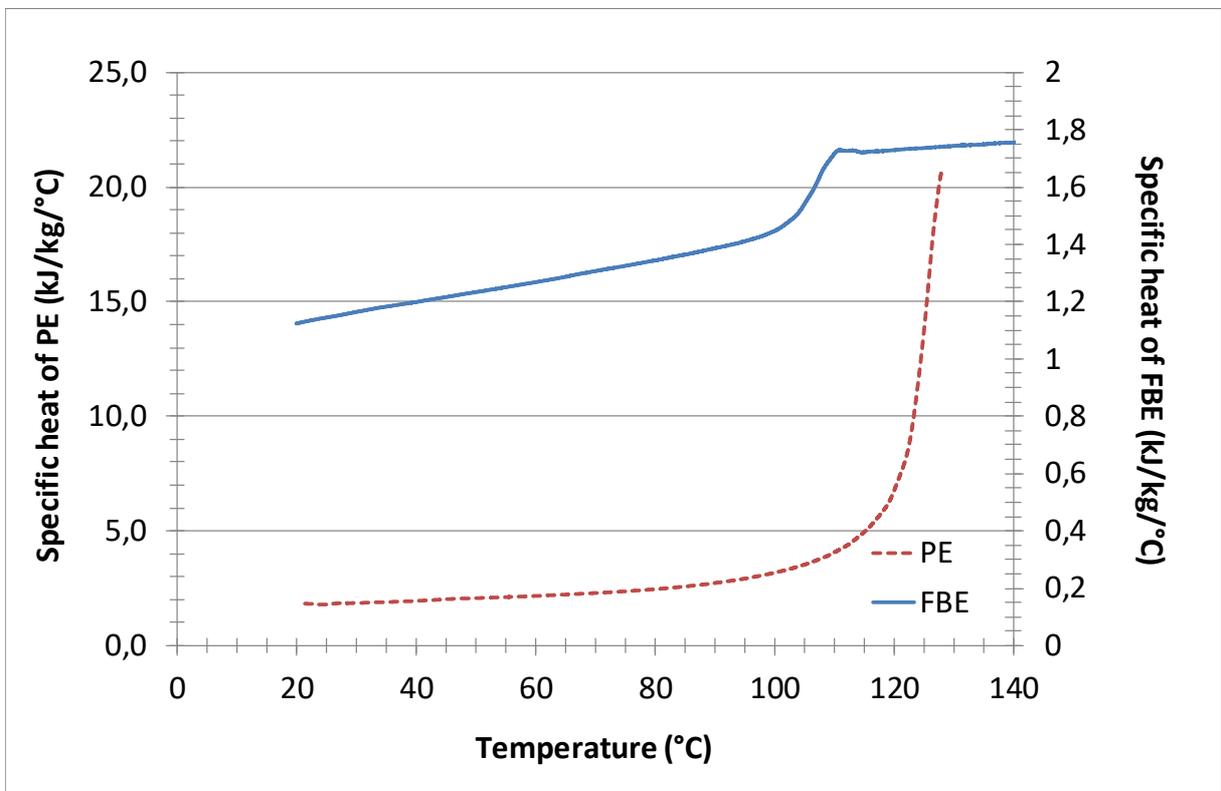


Figure 5: Specific heat as a function of temperature for polyethylene and epoxy (MDSC at 2 K/min)

199
200

201
202

203 **Table 3: WLF parameters of PE and FBE used for the thermo-viscoelastic model [30]**
 204

Materials	T _{ref} (°C)	C ₁	C ₂
FBE	100	12	50
PE	25	16.4	112

205 with T temperature, C₁ and C₂ Coefficient of viscoelasticity

206

207 **Table 4: Numerical parameters of the Prony series to describe the relaxation of PE and FBE at room temperature**
 208

Materials	Parameters of the Prony series (order 3)	1	2	3
PE	g _i	0.3	0.26	0.22
	τ _i	30	1000	1.5
FBE	g _i	0.06	0.064	0.094
	τ _i	1500	10000	100

209

210 The internal stress generated after one year of storage in ambient air at +20°C has been
 211 imported into the numerical model as the initial state of stress [16]. The very small
 212 deformations induced after the relaxation process during the storage period are neglected in
 213 this simulation. The deformation calculated in the radial and longitudinal directions does not
 214 exceed 0.05%.

215 3. Results

216 3.1. Temperature distribution

217

218 Figure 6 shows the temperature distribution in the three-layer coating in service condition for
 219 the three temperature conditions considered (Table 1).

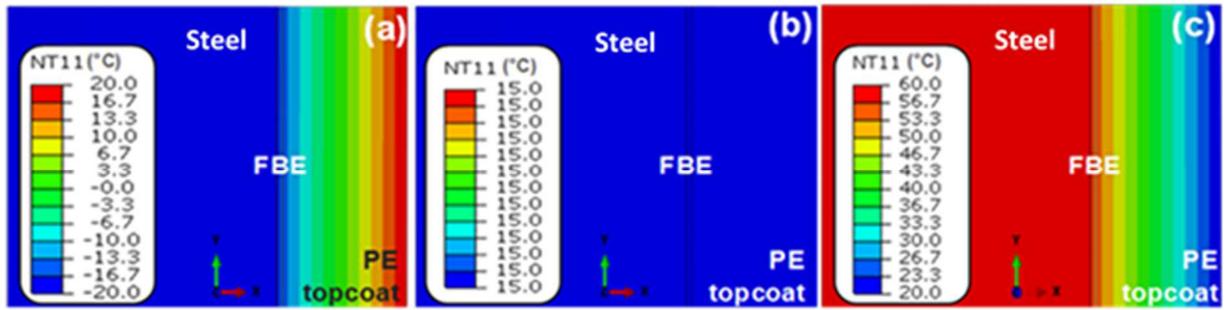
220 PE and FBE are good thermal insulators [41] while steel is a good thermal conductor [42].

221 When gas and soil temperatures differ, a strong thermal gradient is generated between the

222 steel internal surface in contact with the gas and the polyethylene outer surface in contact with

223 the soil (Figure 6 a and Figure 6 c). On the other hand, when the gas and soil temperatures

224 have the same value, a uniform temperature is logically calculated in the pipeline (Figure 6 b).



225

226
227

Figure 6: Temperature isotherms in the pipeline for the 3 cases of thermal conditions considered in Table 1

228 Figure 7 represents the temperature evolution in the pipeline thickness for the three cases

229 studied. In case (a) where the internal temperature of the gas is -20°C and the soil temperature

230 is $+20^{\circ}\text{C}$, the temperature of the steel cylinder varies slightly (between -20°C and -18°C). The

231 steel pipe is practically at the same temperature as the transported fluid. The temperature of

232 the thin FBE insulating layer varies between -18°C and -16°C and the thermal gradient of the

233 thick polyethylene insulating layer is even more marked with a temperature ranging from -

234 16°C (on the inner surface in contact with the FBE) and $+20^{\circ}\text{C}$ (on the external surface in

235 direct contact with the soil). In case (b), where the gas and soil temperatures are equal to

236 $+15^{\circ}\text{C}$, the temperature is the same throughout the thickness of the coated pipeline. As the

237 case (a), in the case (c) where the internal temperature of the gas is $+60^{\circ}\text{C}$ and the soil

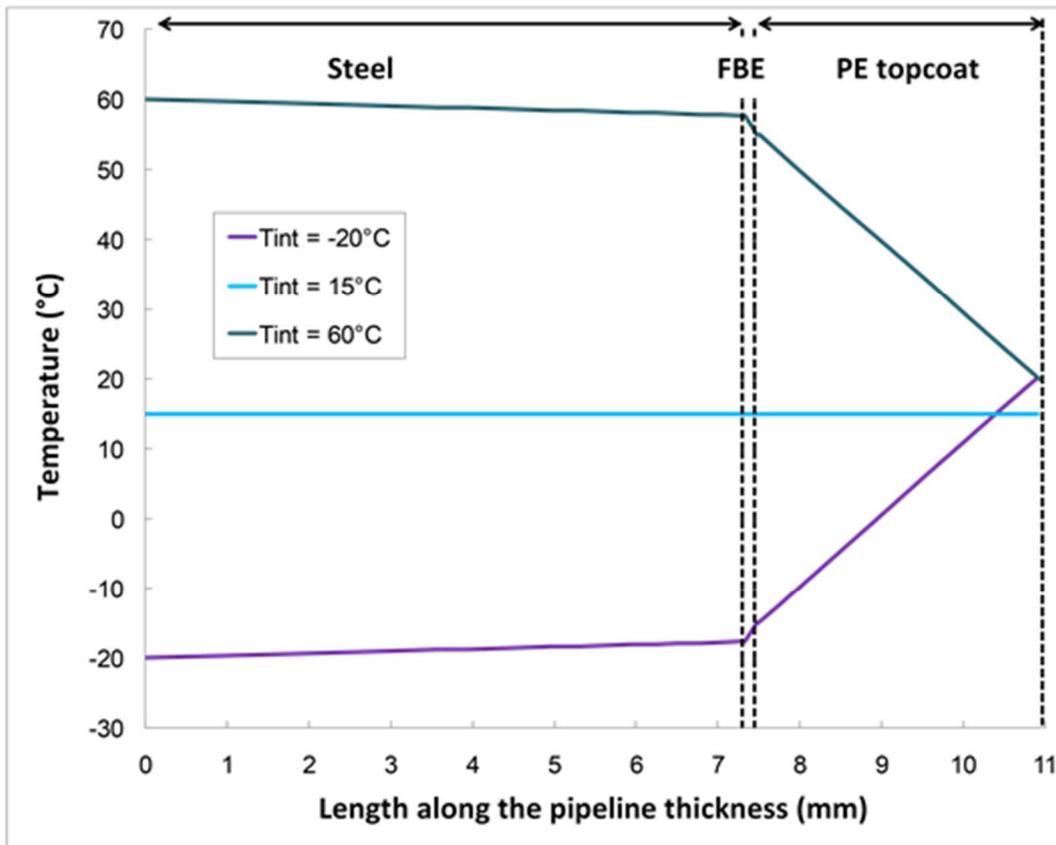
238 temperature is $+20^{\circ}\text{C}$, the temperature of the metal structure varies slightly between $+60^{\circ}\text{C}$

239 and $+58^{\circ}\text{C}$. The temperature of the FBE layer varies between $+58^{\circ}\text{C}$ and $+55^{\circ}\text{C}$ and a strong

240 thermal gradient between $+55^{\circ}\text{C}$ and $+20^{\circ}\text{C}$ is observed in the thick layer of polyethylene.

241 The same temperature gradient is calculated over the entire length of the pipeline.

242



243

244 Figure 7: Evolution of temperatures along the pipeline thickness in service with an internal temperature of -20°C (case a),
 245 +15°C (case b) and +60°C (case c)

246

247 3.2. Stress distribution

248

249 The pipeline network consists of pipes placed end to end and assembled by welding. The

250 assembly of the pipes by welding operation requires to be able to achieve a weld on the whole

251 thickness to ensure a mechanical continuity of the assembly. To achieve this, a bevel

252 (commonly named as “cutback) is made at the end surfaces of the elements to be assembled

253 prior to welding them together [34]. The mechanical operations of removing the coating at the

254 ends of the pipe should modify the stress state at the edges of the three-layers assembly.

255 These phenomena have not been taken into account in this work. Therefore, we will focus on

256 the stresses away from the end of the pipe.

257 Figure 8 presents the stress isovalues based on the Von Mises criterion and the stress

258 isovalues in the circumferential direction (S33) (i.e. direction where the internal pressure is

259 applied). As expected, the internal pressure is mainly supported by the steel pipe.

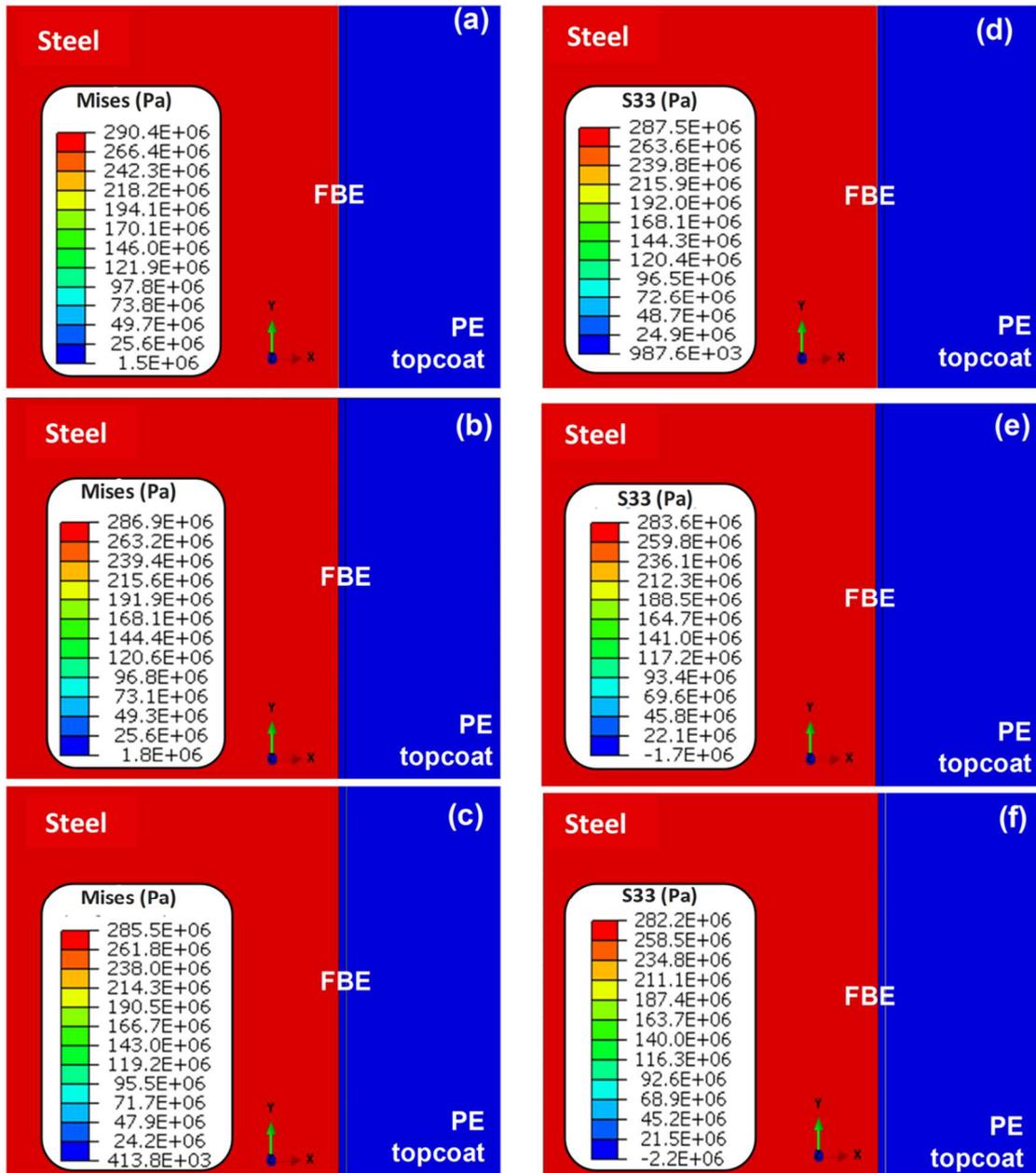
260 In service, the maximum stress calculated in the steel cylinder according to the Von Mises
261 criterion is equal to 290 MPa, 287 MPa or 286 MPa, when the internal temperatures of the gas
262 are respectively set at -20°C ., $+15^{\circ}\text{C}$. or $+60^{\circ}\text{C}$ (Figure 8 a, b, c). In all cases, the maximum
263 stress calculated according to the Von Mises criterion represents approximately 75% of the
264 yield strength of the steel (383 MPa).

265 Furthermore, in the location category 1, at the MOP, the metal structure is sized for maximum
266 stress on the steel pipe at 72% of its yield strength. This restriction is in good agreement with
267 the numerical results which calculate a maximum stress of the metal structure at 75% of its
268 yield strength.

269 Figure 9 shows the isovalues of the stresses away from the ends of the coated pipe in the
270 radial (S11) and longitudinal (S22) directions for the three cases of temperature considered.

271 In the radial direction, the pressure due to the gas on the inner surface of steel cylinder
272 generates compressive stresses in the three-layers coating, which vary linearly between -6.5
273 MPa (value at the inner surface of the steel cylinder in contact with the gas) up to -0.2 MPa
274 (top surface of the steel cylinder in contact with the FBE). In the coating, the radial stresses
275 are almost constant.

276 In the longitudinal direction, when the internal gas temperature is equal to -20°C or $+15^{\circ}\text{C}$,
277 the steel cylinder is in compression and the coating is in tension (Figure 9 d and e). When the
278 internal gas temperature is equal to $+60^{\circ}\text{C}$, the steel cylinder is in tension and the coating is
279 in compression (Figure 9 f). In all cases, the internal gas pressure applied on the steel cylinder
280 generates shear stress at the interfaces and especially at the steel / FBE interface.

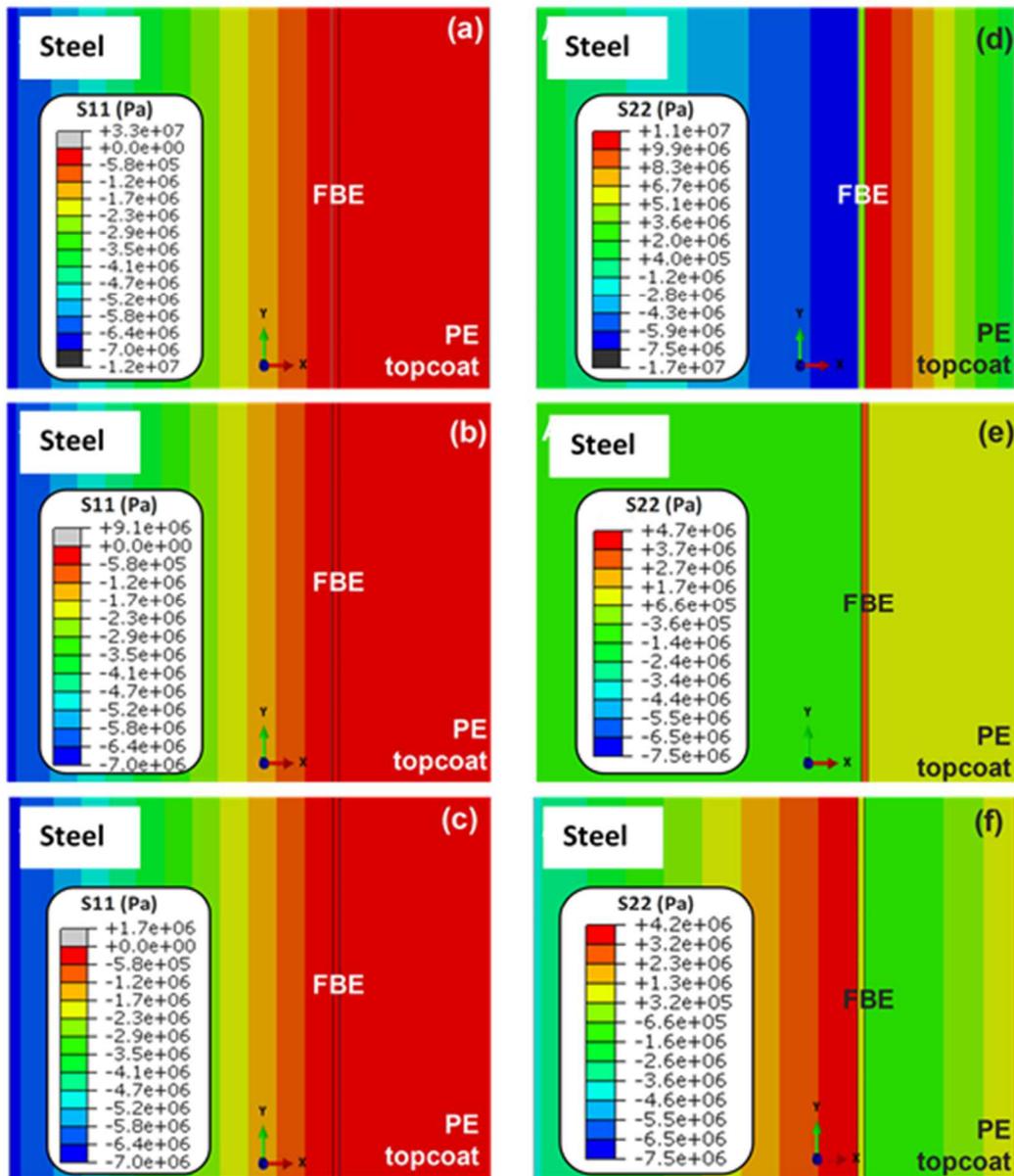


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282

283

Figure 8: Stress isovalues based on the Von Mises criterion (a,b,c) and stress isovalues in the circumferential direction (d,e,f) calculated in case where the gas temperature is (a, d) -20° C, (b, e) +15° C and (c, f) +60° C



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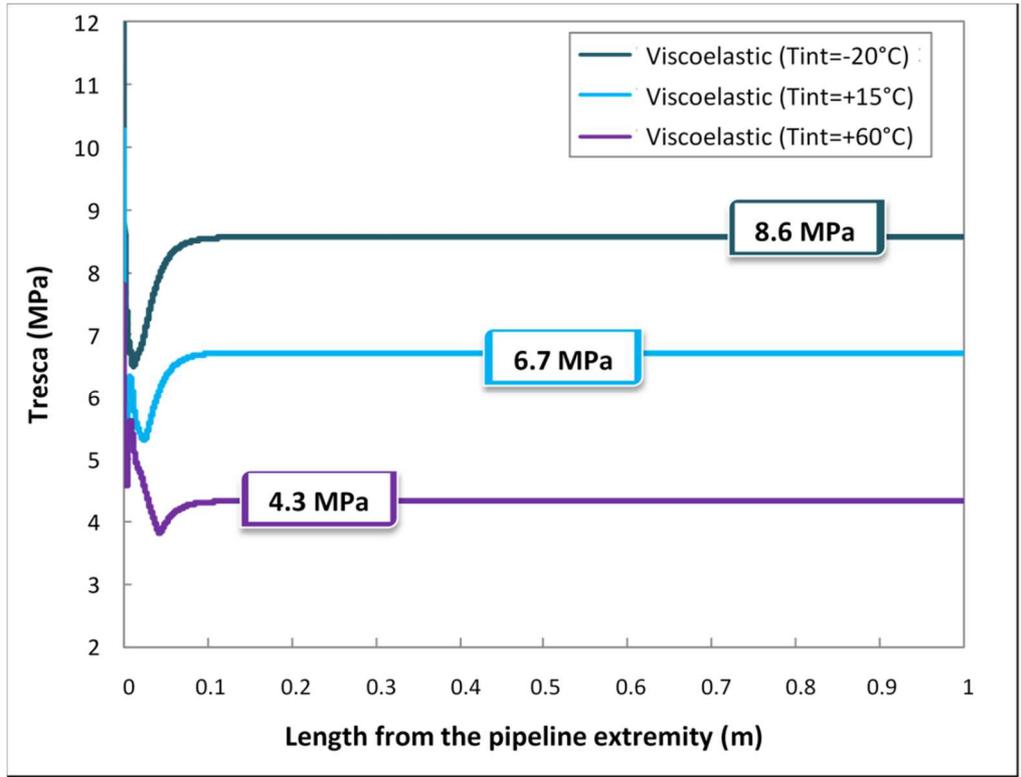
285 Figure 9: Radial (S11) (a,b,c) and longitudinal (S22) (d,e,f) stress isovalues calculated when gas temperature is (a,d)-20° C,
 286 (b, e) +15° C and (c, f) +60° C

287

288 As shear phenomena are mainly present at the interfaces, the Tresca criterion has been chosen
 289 to follow the stress evolution along the interfaces. It is important to remember that the
 290 classical criteria, as Von Mises or Tresca, are understood to be appropriate for pressure-
 291 insensitive materials (as steels for example), the pressure-sensitivity (in fracture, damage and
 292 yielding) of polymers often requires more advanced equivalent stress measures (as Drucker-
 293 Prager for example). Figure 10 and Figure 11 describe the evolution of the stresses calculated

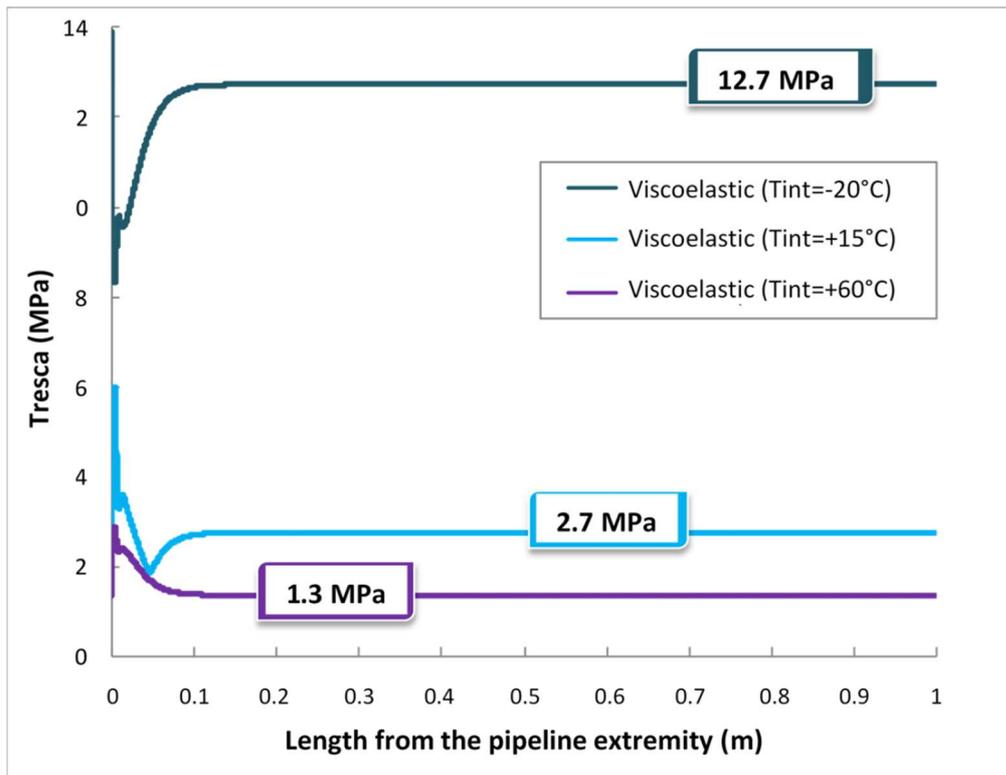
294 according to the Tresca criterion at the steel/FBE interface and at the PE/FBE interface
295 respectively.

296



297

298 **Figure 10: Evolutions of the stresses calculated in the FBE layer along the steel / FBE interface on a pipeline coated in**
299 **service with an internal gas temperature of -20° C, +15° C or +60° C**



300

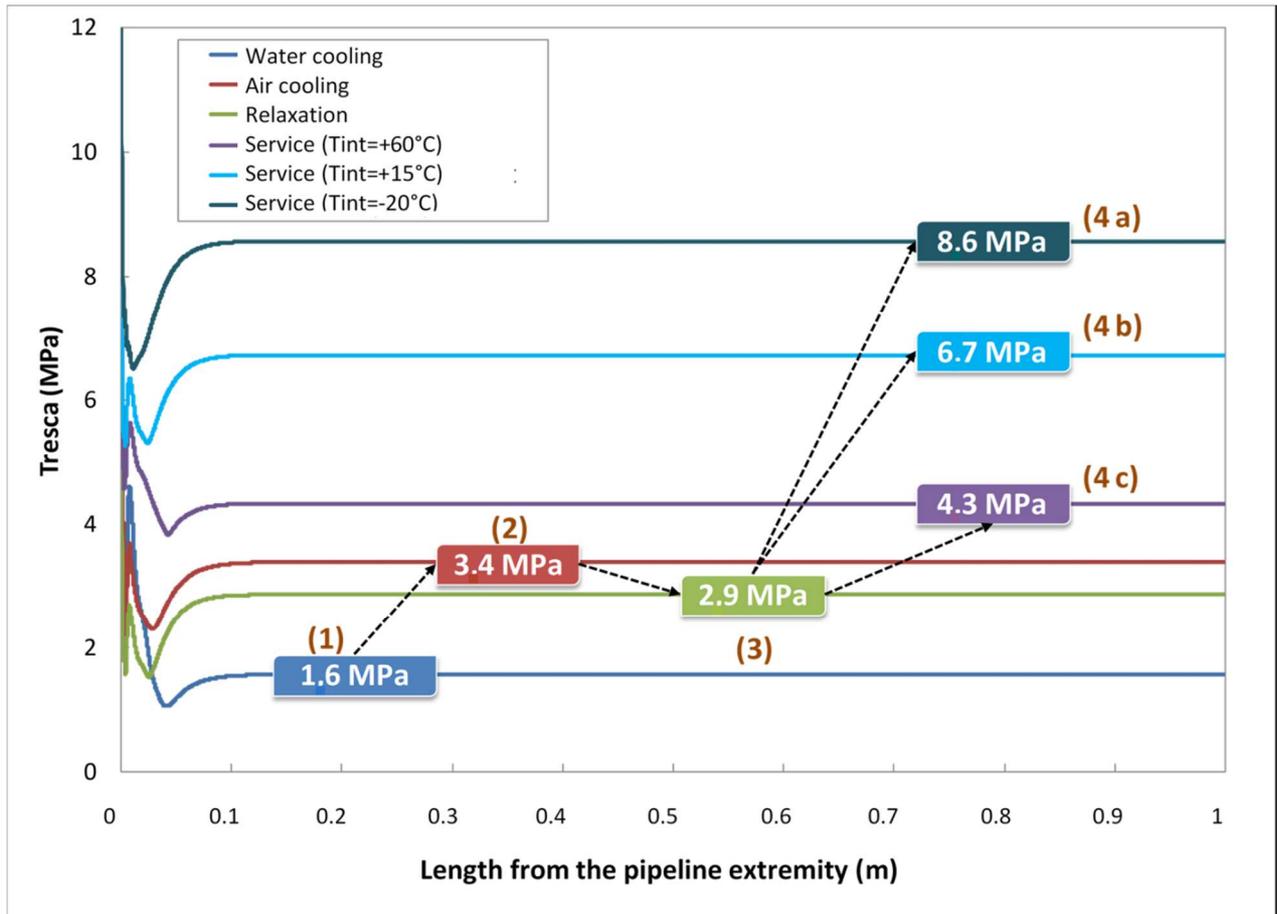
301 **Figure 11: Evolutions of the stresses calculated in the PE layer along the PE / FBE interface on a pipeline coated in service**
 302 **with an internal gas temperature of -20° C, +15° C or +60° C**

303

304 In the three cases studied, the internal pressure generated on the steel cylinder is the same.
 305 However, the thermal environments are different. The numerical results show that the most
 306 critical temperature distribution is calculated when the internal gas temperature is -20°C and
 307 the soil temperature is +20°C. In this case, stresses are respectively 8.6 MPa and 12.7 MPa at
 308 steel/FBE and PE/FBE interfaces. Lower stress levels are obtained when the temperature of
 309 steel increases (decrease of the value of the differential thermal expansion between the
 310 different layers of the pipeline structure).

311 The stresses at steel/FBE and PE/FBE interfaces are respectively 6.7 MPa and 2.7 MPa when
 312 the internal temperature is +15°C. Stress values decrease up to 4.3 MPa and 1.3 MPa
 313 respectively, when the internal temperature of steel is at +60°C. Furthermore, when the
 314 temperature of steel is at +60°C, the temperature of the FBE layer varies between +58°C and
 315 +55°C and PE layer temperature varies between +55°C and +20°C. However, around +55°C,

316 the Young's modulus of the FBE is equal to 2.6 GPa ($E_{\text{FBE}} = 2.9$ GPa at room temperature).
317 The Young's modulus of PE varies from 1 and 0.7 GPa between +20°C and + 55°C. So there
318 is certainly an effect of the drop of polymer mechanical properties with the temperature.
319 When the gas temperature is greater than or equal to +15°C, the stresses at the steel/FBE
320 interface are always greater than the stresses at the PE/FBE interface. On the other hand,
321 when the gas is injected into the pipeline at low temperature and especially at - 20°C, the
322 stress levels are higher at the PE / FBE interface.
323 Figure 12 compares the calculated stress levels with the thermo-viscoelastic model at the
324 steel/FBE interface from manufacture to use in service conditions. The manufacturing of the
325 three-layer coating is simulated by cooling the assembly with water (step 1) and then with air
326 (step 2). The storage of the tube coated for one year in the ambient air takes into account the
327 stress relaxation with time (step 3). The operation is simulated with a pressure applied on the
328 inner surface of the steel cylinder and an internal temperature of steel fixed at -20°C, +15°C
329 or +60°C (step 4 a, b or c). The study always focuses on stress levels away from the end of the
330 pipe.

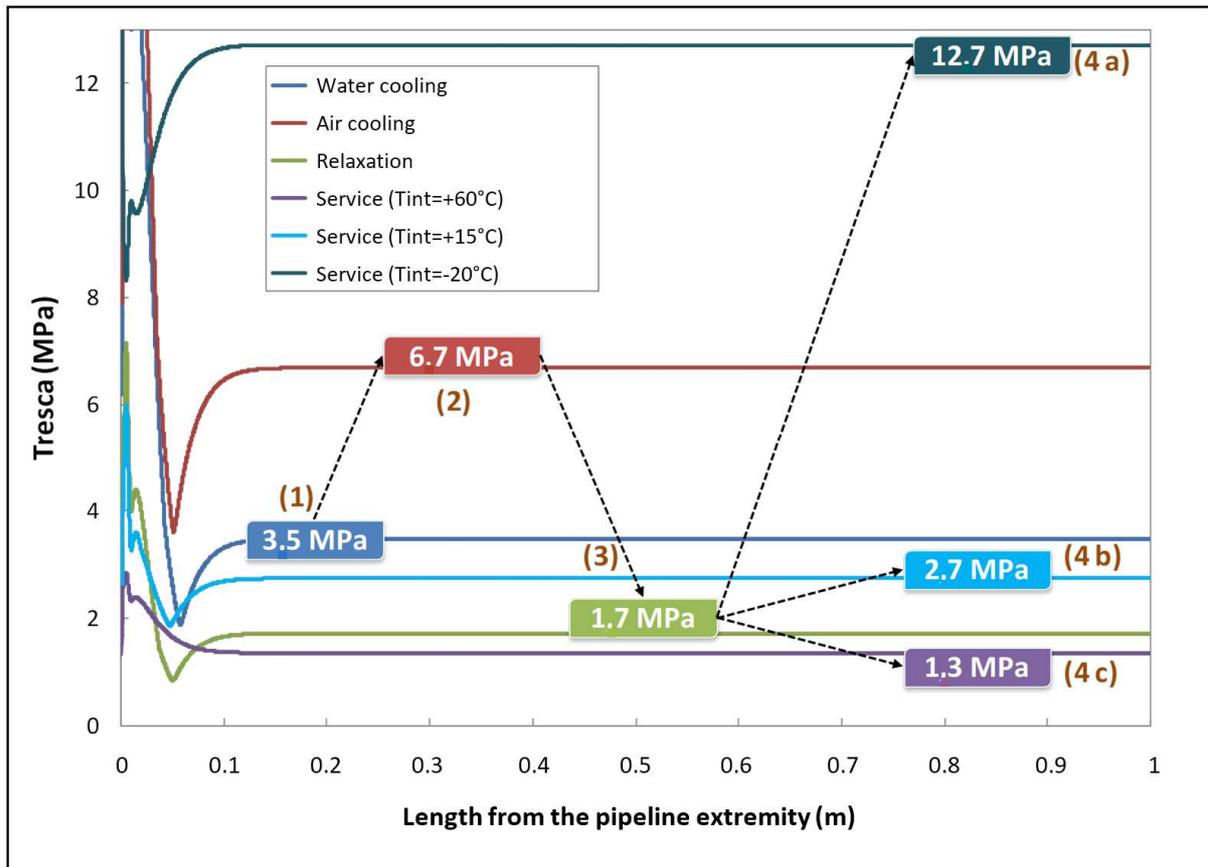


331

332 **Figure 12: Evolution of the stresses calculated according to the Tresca criterion at the steel / FBE interface during the**
 333 **different stages of the pipeline life**

334 In agreement with the previous results [12,30], after the coating process, the stresses at the
 335 steel/FBE interface increase from 1.6 MPa to 3.4 MPa due to the successive cooling stages
 336 (water and air cooling). During one year of storage, a low relaxation of the FBE layer leads to
 337 a slight decrease of the interfacial stress down to 2.9 MPa. In service, the gas pressure and
 338 temperature gradients within the pipe result in increased shear stresses along the steel/FBE
 339 interface. Stress can reach values greater than or equal to 4.3 MPa.

340 Similarly, Figure 13 compares the calculated stress levels from the thermo-viscoelastic model
 341 in the PE/FBE interface at the different stages of the pipeline life.



342

343 **Figure 13: Evolution of the stresses calculated according to the Tresca criterion at the PE / FBE interface during different**
 344 **stages of the pipeline life**

345

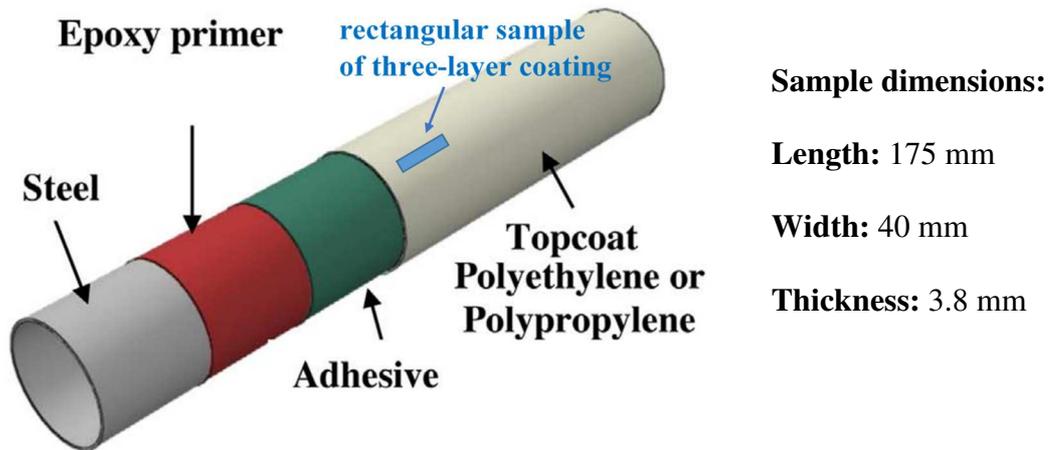
346 As with the steel/FBE interface, the stress at the PE/FBE interface strongly increases from 3.5
 347 MPa to 6.7 MPa during the cooling step. The high relaxation capability of polyethylene
 348 allows a relaxation around 75% of the stresses generated in the PE layer. Finally, the stress is
 349 only 1.7 MPa after one year of storage. According to the temperatures applied to the pipeline
 350 in service conditions, the stresses at the PE/FBE interface may be lower or higher than the
 351 residual stresses after one year of storage. In all cases, they are greater than or equal to 1.3
 352 MPa.

353 When the internal temperature of the steel is equal to +60°C, the relaxation phenomena of the
 354 PE are predominant and the stresses reach up to 1.3 MPa. On the other hand, when the
 355 temperature of the injected gas is less than or equal to +15°C, shear stress developed at the
 356 PE/FBE interface, becomes predominant and the stresses are then greater than those

357 calculated after one year of storage. They are respectively equal to 2.7 MPa or 12.7 MPa
358 depending on the gas temperature (+ 15°C or -20°C). In service, when gas temperature is
359 equal to - 20°C, the stresses become greater than the internal stresses generated by the coating
360 process. It would be interesting to particularly monitor the condition of the coatings in these
361 areas of the pipeline network in service. Nevertheless, these stresses remain much lower than
362 the tensile strength of PE (35-40 MPa) [4] or the shear strength of PE (25-30 MPa) [5]. Until
363 now, previous studies have concluded in a state of residual stress (post process) of a few units
364 of MPa. However, Legghe [43] was demonstrated that the adhesion losses of the coating were
365 directly correlated with the arrival times of water at the steel / FBE interface, with adhesions
366 residuals of 2-10 MPa on rough substrates. The origin of the disbonding could come from the
367 consequence of this loss of property in service and of a non-negligible state of internal stress.

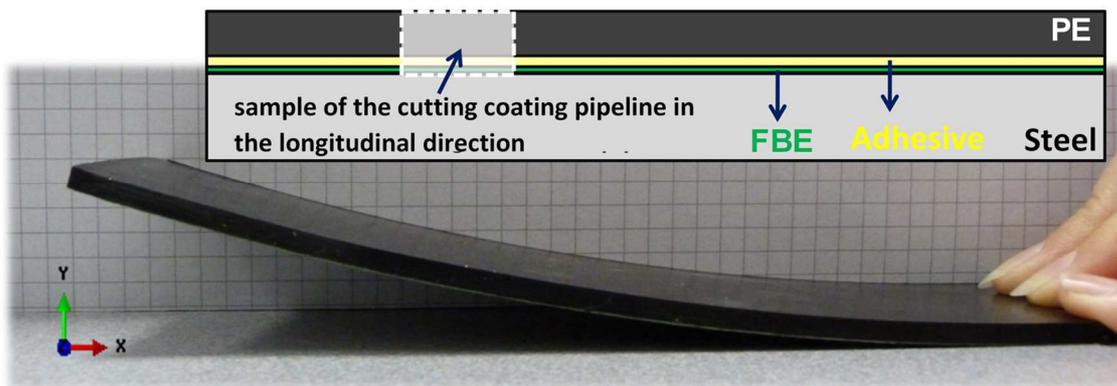
368 **4. Reliability of the numerical approach based on pipeline diagnostics**

369
370 The internal stresses stored in the three-layer coating of a pipe in service for 6 years and with
371 no adhesion between the coating and steel have been evaluated. A rectangular sample of
372 three-layer coating has been cut in the longitudinal direction of the pipe (Figure 14). The
373 planar sample is rapidly curved during storage at room temperature. This deformation is due
374 to the presence of internal stresses stored in the coating during the process. Zhu et al. [42]
375 have shown by image correlation and by finite element the curvature generated by the
376 presence of a stress gradient in a multilayer material. Moreover, the generated curvature
377 proves the presence of stress gradient in the coating. Figure 15 shows the deformed geometry
378 of the sample 24 hours after cutting.



379 **Figure 14:** rectangular sample of three-layer coating cutted in the longitudinal direction of the pipe

380



381

382 **Figure 15:** Visualization of the deformation in the coating 24h after cutting

383 In order to quantify these internal stresses, the geometry of the deformed coating is

384 reproduced in the ABAQUSTM/standard solver. The objective is to simulate a return to the

385 planar shape of the curved sample and to quantify the stress associated with this operation. A

386 linear elastic approach is used to estimate the stress in the pipe coating in service.

387 **4.1. Model 1 based on mechanical loading**

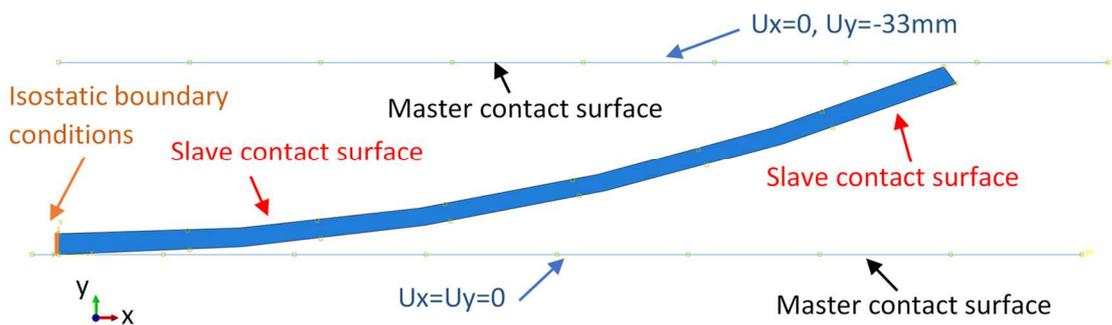
388

389 The numerical model developed is directly inspired by the numerical model used for stamping

390 process. **In this case, a rigid tool will come and press the curved sample so that it regains a**

391 **planar shape (ie initial shape after the coating process).** Numerical model is based on a

392 deformable part (coating curved) and 2 rigid parts (down and top tools – blue line Figure 16).
 393 The down rigid part is used as bearing surface for the sample, the second is used to apply a
 394 vertical displacement to the curved coating. Interactions between each solid part are managed
 395 by 2 contacts as described on Figure 16. A "surface to surface contact" has been chosen, with
 396 the assumption of perfect sliding properties between the tool surface and the surface coating.
 397 Isostatic boundary conditions - cancellation of degree of freedom to block the displacement of
 398 the sample without adding stresses, i.e. displacement of orange line $U_y = 0$ and displacement
 399 of a point of this line $U_x = 0$ - are imposed as shown in Figure 16. When one end of the curved
 400 coating is maintained on a plan surface, the other end is located at 33 mm from the plan
 401 surface. So, a displacement of -33 mm is therefore applied on top of the rigid part.

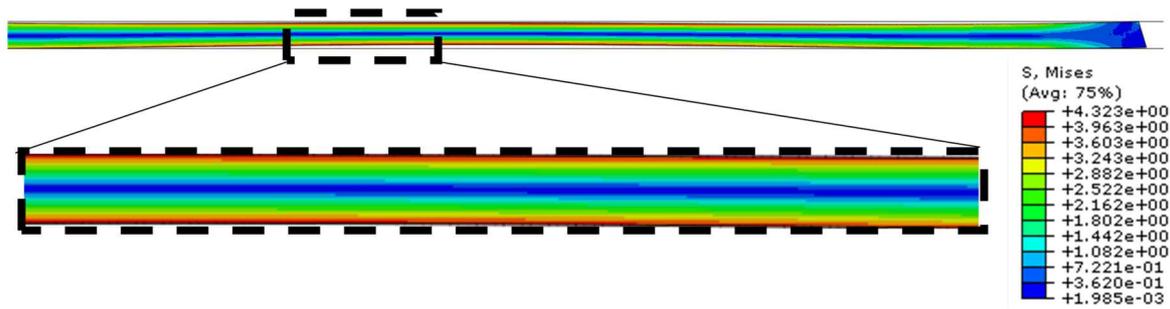


402
 403 **Figure 16: Boundary conditions and loading applied on the numerical model**

404 A 2D model, using quadrangular elements with quadratic interpolation (CPS8), is carried out.
 405 The mesh is made by the "Structured" technique. The discretization of the curved geometry
 406 was carried out by 200 nodes in the length of the sample and 5 nodes in the thickness of the
 407 coating, to give a total number of 1000 elements.

408 Figure 17 presents the numerical results of the stresses calculated from the Tresca criterion.
 409 The result show that maximum stress around 4-5 MPa has been calculated in the coating. This
 410 value can be considered as the value of stress (elastic stress) present in the coating in service.
 411 These stress values are consistent with the stress levels estimated previously (Figure 12),

412 between 4 and 9 MPa at the steel/FBE interface (function of temperature and pressure cases).



413

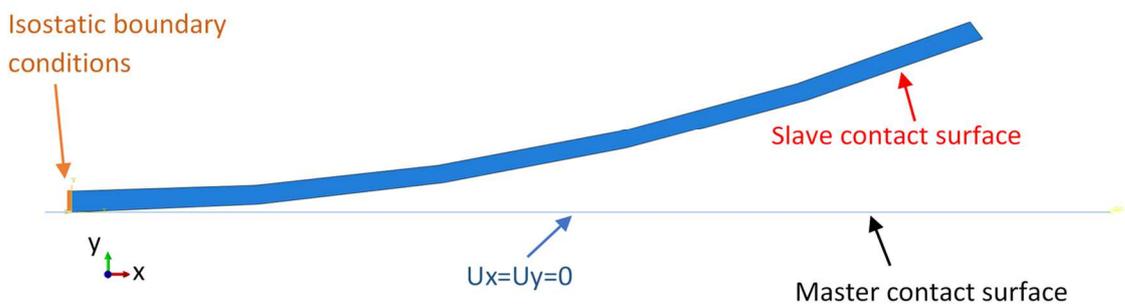
414 **Figure 17: Isovalues** of the stress values in the radial and longitudinal directions and Tresca criteria (MPa) after recovery
415 of the sample (mechanical loading)

416

417 4.2. Model 2 based on thermal loading

418

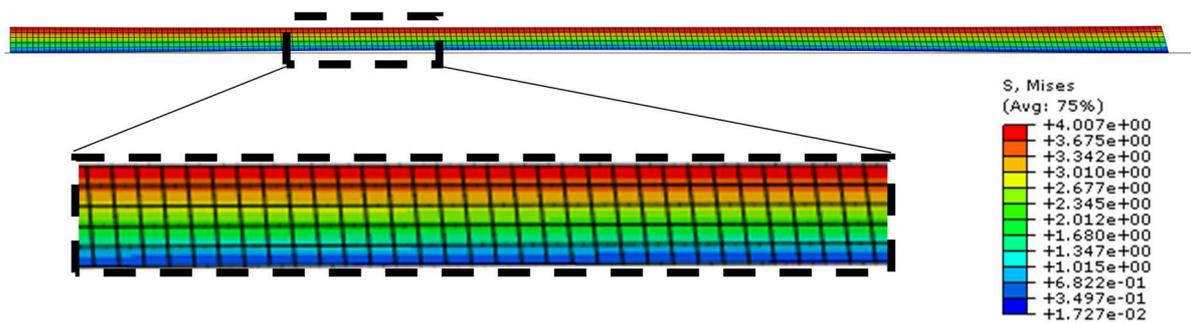
419 In the assumption that the stresses come mainly from the coating process, a second model has
420 been developed directly inspired from the process stage. The idea is to apply a temperature on
421 the upper surface of the sample in order to reproduce the thermal gradient allowing a return to
422 a **plan** position of the sample. In this case, numerical model is based on a deformable part
423 (coating curved) and only one rigid part (bearing surface of the sample – blue line Figure 17).
424 Contact properties are identical to model 1 (model based on mechanical approach). Isostatic
425 boundary conditions are imposed as shown in Figure 17. A temperature is imposed ($T = 55^{\circ}\text{C}$
426 – hot temperature value at the end of the coating process) on the upper surface of the sample
427 while the lower surface is maintained at room temperature ($T = 20^{\circ}\text{C}$).



428

429 **Figure 18: Boundary conditions and loading applied on the numerical model**

430 A 2D thermomechanical model, using quadrangular elements with quadratic interpolation
431 (CPE8RT), is carried out. The mesh is made by the "Structured" technique with an element
432 size similar to the previous model.
433 Figure 19 presents the numerical results of the stresses calculated from the Tresca criterion.
434 The result show that maximum stress around 4 MPa has been calculated in the coating. This
435 value confirms the previous results on the order of magnitude of the residual stress in the
436 coating.



437
438 **Figure 19: Isovalues of the stress values in the radial and longitudinal directions and Tresca criteria (MPa) after recovery**
439 **of the sample (thermal loading)**

441 5. Conclusion

442
443 This study has shown that the pressure and the temperature are favourable to decrease the
444 shear stress at the different interfaces present in the three-layers coating. In service, the
445 interfacial stresses are therefore generally greater than the residual stresses after storage of the
446 coated tube at ambient temperature (except at PE/FBE interface, in the case where the
447 temperature of the gas is +60°C). When the gas is injected at a low temperature (-20°C),
448 which is particularly the case at the exit of the compressor stations, the highest stresses are
449 observed at PE/FBE interface. On the other hand, when the gas is injected at a higher
450 temperature (+15°C or +60°C), which is the case on most of the transportation network, the
451 highest stresses are at the steel/FBE interface which is therefore the most critical interface.
452 Furthermore, an industrial feedback (coating sample of three-layer coating cutted in the

453 longitudinal direction of the pipe) has allowed us to estimate that the stresses in the coating
454 are between 4 and 5 MPa for the three-layers coating. These values are consistent with the
455 stress levels estimated, between 4 and 9 MPa at the steel/FBE interface, obtained by
456 successive modelling of the different steps of pipeline life (coating process, pipeline storage
457 and service conditions). Moreover, this feedback helps to validate the numerical model
458 developed in this project due to the small difference observed between these numerical
459 results.

460 However, this study can not fully explain the debonding cases observed occasionally between
461 the three-layers coating and the steel cylinder. One possible cause could be the loss of
462 interface performance due the combination with aging phenomena, especially with the water
463 diffusion from the soils across the polymer coating up to the steel/FBE interface.

464

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466

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469

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