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Influence of Strain Aging on Parameters for Assessment of Multi-Axial Load Histories of High-Frequency-Induction (HFI) Welded Line Pipe

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ABSTRACT

The elevated attention to a resource- and cost-saving installation and safe operation of pipelines has led to the development of the strain-based design strategy. Although different theoretical models have been developed and calculation approaches transferred to standards, the pipeline's resistance to such load scenarios, which induce pronounced longitudinal strains and multi-axial stress-strain states in combination with internal pressure, is not fully solved. The anisotropy of HFI-pipes as well as the alteration of the mechanical properties of the pipe material caused by coating is presented in this paper. In addition the impact on the pipe behaviour under multi-axial stress-strain states is compared and discussed by using the own developed analytic model.

KEY WORDS:

Multi-axial stress-strain; anisotropy; HFI-pipes; modelling; coating; compression; bending

NOMENCLATURE

A_5	elongation at break
A_g	uniform elongation
C_H	constant (Hollomon)
$k(\varepsilon_v^p)$	function of the plastic strain
OD	outer diameter
p_i	internal pressure
p_{SMYS}	pressure related to $SMYS$
R_m	tensile strength
$R_{t0.5}$	yield strength at 0.5 % strain
$SMYS$	specified minimum yield strength
t	wall thickness
Y/T	ratio of $R_{t0.5}/R_m$
n_H	strain hardening exponent (Hollomon)
$\varepsilon_{critical}$	critical strain
ε_v	maximum strain value
$\sigma_{d3.0}$	compression strength at 3.0 % strain
$\sigma_{d0.5}$	compression yield strength at 0.5 % strain

INTRODUCTION

The growing demand for energy worldwide over the last decades has resulted in an increase in the exploration and exploitation of natural gas and oil resources in remote environments under aggravated conditions. Additionally, elevated attention has been turned to a resource- and cost-saving installation and operation of pipelines. At the same time an accelerated increase of safety awareness can be observed, in order to prevent environmental or population damage. This led on the one hand to an advanced ability of pipe producers for manufacturing of pipes with an increased wall thickness. For economic reasons high-strength steels for reducing pipe wall thickness or increasing the operation pressures of transportation pipelines were developed on the other hand. Pipeline designers tend more and more to take into consideration not only the material property requirements during pipe laying (e.g. reeling), but also the need for safe pipeline operation especially in more serious geological environments, for example seismically active regions, landslide zones, regions with discontinuous permafrost, soil subsidence, frost heave or thermal expansion and contraction. These severe application environments can cause large ground movements, which hence can create large plastic deformations of the pipeline and, in worst case, result in catastrophic pipe failure. In order to avoid this, pipelines are nowadays often designed not only using the conventional stress-based design method for cases, where pipelines are exposed to a higher level of stress in the circumferential direction than in the longitudinal direction (i.e. under internal pressure). This method, limiting the maximum stress to a lower value than the specified minimum yield strength, does not take into account the occurrence of environmental deformation, when the applied strain, mainly in longitudinal direction of the pipeline, exceeds the elastic limit of the material. To encounter this challenge of potential failures driven by high longitudinal strains, the strain-based design strategy is employed. This covers cases where the loading mode is displacement controlled. It allows the pipe to deform plastically in order to reduce the stresses in the pipe material. Following this, the pipeline steel must not only have the capability to withstand demanding operating conditions like high internal pressure, but has to show also sufficient deformation resistance.

MATERIAL ANISOTROPY AND STRAIN AGING BEHAVIOUR OF HFI-WELDED PIPES

The material properties in longitudinal and transverse direction as well as tensile and compression characteristics influence the pipe behaviour when subject to external loads, e.g. bending. Therefore the determination of anisotropy of the material becomes essential for calculation of critical strain-based design parameters [Hilgert et al., 2012; Hart et al. 2012]. Strain aging of the steel also has to be considered. It is time and temperature dependent and can occur during the standard polymer- or FBE- (fusion bonded epoxy) coating treatment of the pipe where the temperature of the linepipe can reach 250 °C for several minutes. This causes thermal aging because of the cold pre-deformation during pipe forming process [Zheng et al., 2012]. During the heating process small atoms like carbon or nitrogen diffuse to dislocation cavities and impede dislocation movement, resulting in higher forces necessary to allow plastic deformation by activation of the cleavage planes. [Berns and Theisen, 2010; Noecker et al., 2012]. The mechanical properties such as yield strength, tensile strength, *Y/T*-ratio, uniform elongation and stress-strain curve shape can change due to thermal aging. Additionally for older linepipe steels an embrittlement of the pipe material can occur, due to sub microscopic precipitation on the cleavage plane of the crystals grains [Pense, 2004].
In order to determine the anisotropy as well as the strain-aging resistance of HFI-welded pipes, extensive mechanical characterisation tests of the base material have been carried out. **Table 1** shows an overview of the grades and dimensions that have been included up to now.

Table 1: Overview of the investigated grades and dimensions

X52		X60		X65	
OD in mm	*t* in mm	*OD* in mm	*t* in mm	*OD* in mm	*t* in mm
273.0	8.18	457.0	7.1	273.1	12.7
273.0	9.2	508.0	15.9	323.9	15.9
273.0	10.0	406.4	9.5	406.4	9.5
323.9	9.5	406.4	16.0	406.4	10.3
406.4	6.2			406.4	12.5
406.4	6.3			406.4	17.5
406.4	12.5			609.6	12.7
406.4	12.7				
406.4	20.0				
508.0	20.6				

Specimen orientation

In all investigations round specimens according to DIN 50125 [DIN50125] have been used. As the yield-to-tensile ratio affects the tensile properties of both uncoated and coated pipes, it is given next to the mean values in the following figures. It becomes obvious that the tensile specimens taken longitudinally to the pipe axis exhibit a higher yield strength compared to the specimens taken transversely to the pipe axis (**Figure 1**). As for the tensile strength R_m only a trend of higher values for transverse direction can be noticed (**Figure 2**), the yield-to-tensile ratio $R_{t0.5}/R_m$ relates mostly to the yield strength. Lower values are determined for transverse direction (**Figure 3**). In addition to the elevated tensile strength in transverse direction the uniform elongation A_g in transverse direction tends to be higher for most cases than in axial pipe direction (**Figure 4**).
In contrast to the tensile tests, the compression-test specimens taken transversely to the pipe axis of the non-coated pipes exhibit higher compression yield strength than the compression-test specimens taken longitudinally to the pipe axis (**Figure 5**). The pipe forming process can be identified as the reason for this characteristic behaviour [Zimmermann et al., 2004]. At the end of pipe forming the diameter of the HFI-pipe is slightly plastically reduced by the use of a compression step. With this calibration in the circumferential direction the so-called "Bauschinger effect" is accompanied and is also responsible for lower yield strength in tensile tests compared to compression tests. On the other hand the Bauschinger-effect affects the mechanical properties of the pipe in longitudinal direction contrary to the transverse direction. A plastic elongation of the pipe string is associated with the strip-to-pipe forming and final calibration process. The similar values for tensile and compression yield strength in longitudinal direction illustrate the uniform pipe forming process concerning the longitudinal pipe direction.

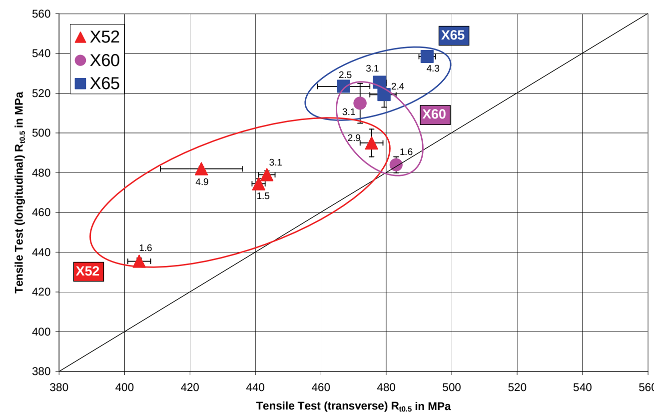

Figure 1: Comparison of yield strength $R_{t0.5}$ in tensile tests on round specimens taken in transverse and longitudinal direction as a function of the material grade (mean values and range)

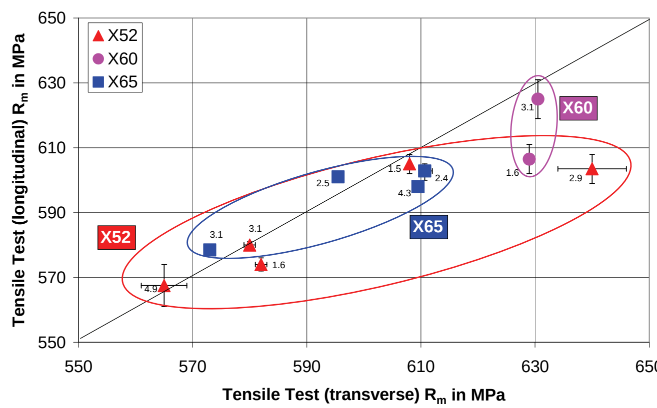

Figure 2: Comparison of tensile strength R_m in tensile tests on round specimens taken in transverse and longitudinal direction as a function of the material grade (mean values and range)

Coating

A series of small-scale tests on specimens out of HFI-welded pipes were performed to evaluate the effect of thermal aging due to the pipe coating process, e.g. a three layer Polyethylene (PE) coating at about 210 °C. In most of the cases the coating process tends to result in an increased yield strength $R_{t0.5}$ as well as a higher tensile strength R_m (**Figure 6**). It can be assumed, that a possible explicit behaviour is masked by the variation of tensile values for grades X60 and X65. Some characteristic stress-strain curves of grade X65, not affected by the coating process, demonstrate this (**Figure 7**). As the amount of the increase in strength is nearly identically for both characteristic parameters, the yield-to-tensile ratio $R_{t0.5}/R_m$ is thus not much affected by thermal aging. At the same time the compression yield strength $\sigma_{d0.5}$ is found to be decreased by the aging process, whereas $\sigma_{d3.0}$ increases (**Figure 8**). This is due to a change of the stress-strain curves to a more round-house shape, caused by the thermal aging effect during coating (**Figure 9**). The change in strength under compressive load due to thermal aging causes the yield-to-tensile ratio $\sigma_{d0.5}/\sigma_{d3.0}$ to decrease after coating (**Figure 10**). Concurrently the ductility is more or less not altered compared to the non-coated condition (**Figure 11**). It seems that the elongation at break for grade X65 is slightly reduced by the coating process. All these findings are consistent with investigations also of other types of pipe (e.g. UOE, seamless) [Liessem et al., 2004; Noecker et al. 2012; Zheng et al., 2012; Shitamoto et al., 2012].

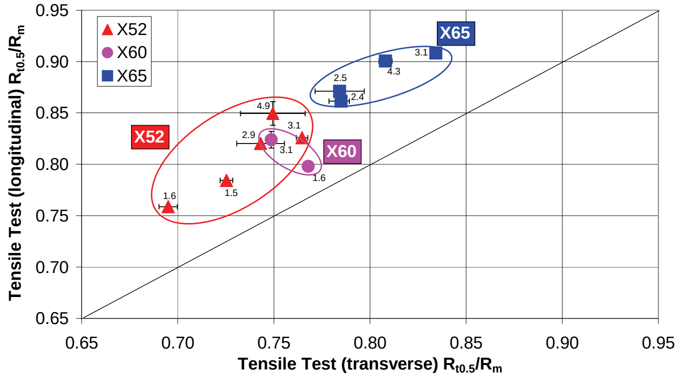

Figure 3: Comparison of yield-to-tensile ratio $R_{t0.5}/R_m$ in tensile tests on round specimens taken in transverse and longitudinal direction as a function of the material grade (mean values and range)

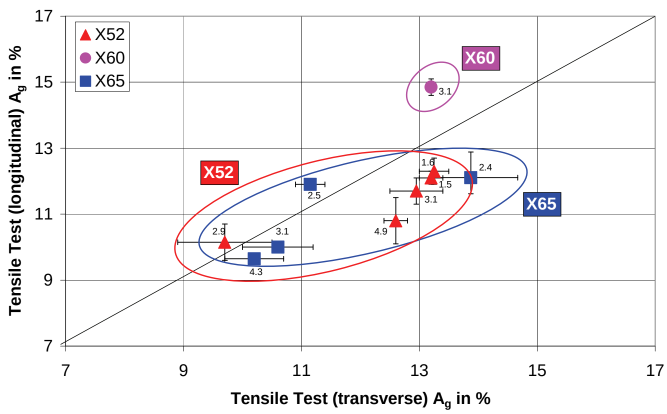

Figure 4: Comparison of uniform elongation A_g in tensile tests on round specimens taken in transverse and longitudinal direction as a function of the material grade (mean values and range)

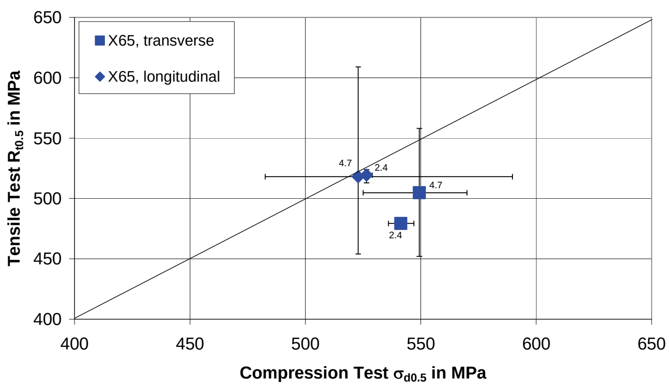

Figure 5: Comparison of yield strength in tensile ($R_{t0.5}$) and compression ($\sigma_{d0.5}$) tests on round specimens taken in transverse and longitudinal direction of the material grade X65 (mean values and range)

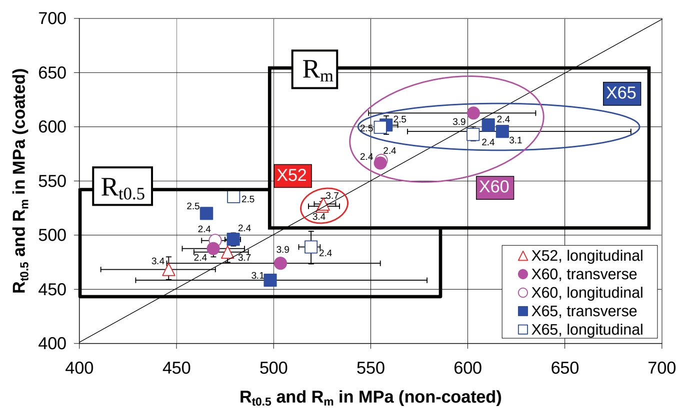

Figure 6: Comparison of $R_{t0.5}$ and R_m between non-coated and coated pipe as a function of the material grade and specimen orientation

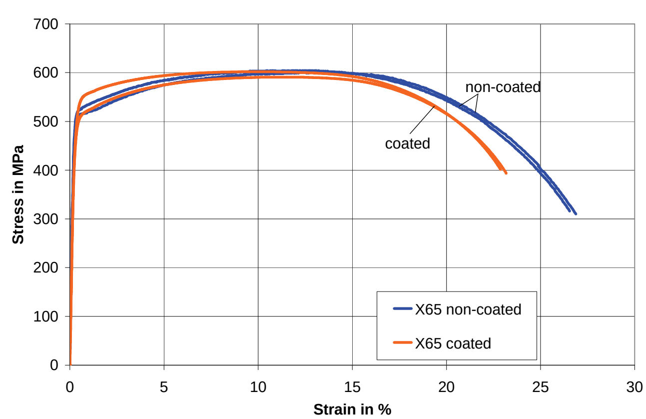

Figure 7: Tensile stress-strain curves (examples) of non-coated and coated pipes (grade X65, longitudinal test direction)

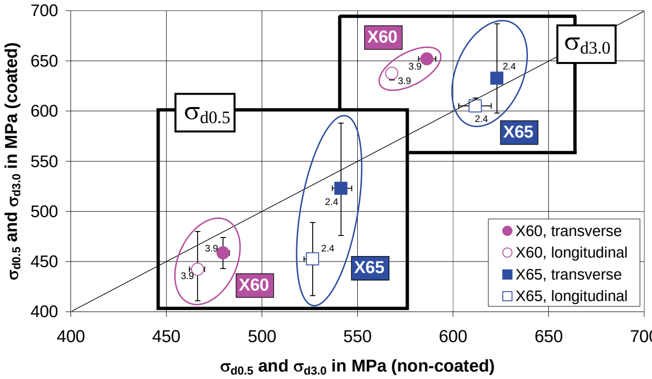

Figure 8: Comparison of $\sigma_{d0.5}$ and $\sigma_{d3.0}$ between non-coated and coated pipe as a function of the material grade and specimen orientation

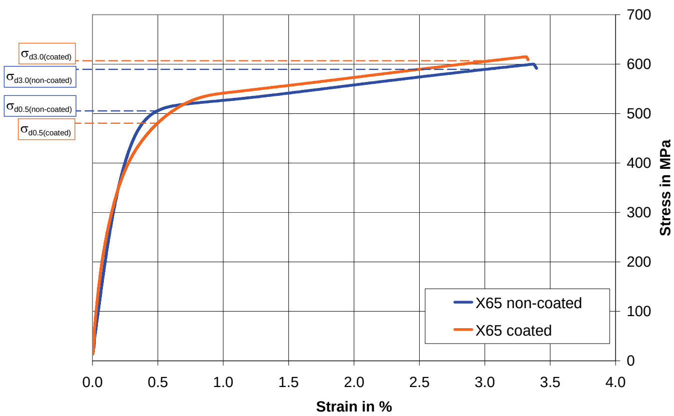

Figure 9: Compressive stress-strain curves (examples) of non-coated and coated pipe (grade X65, longitudinal test direction)

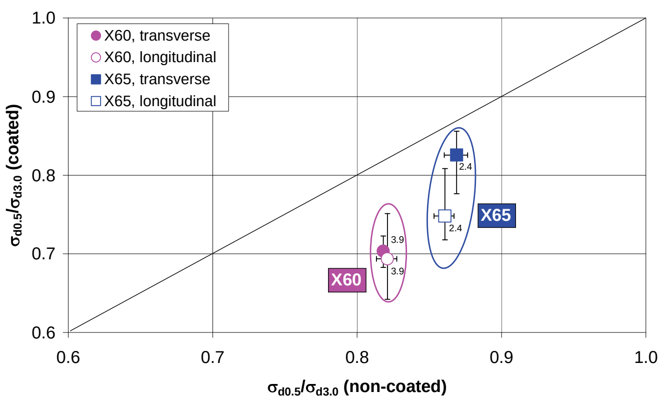

Figure 10: Comparison of $\sigma_{d0.5}/\sigma_{3d3.0}$ between non-coated and coated pipe as a function of the material grade and specimen orientation

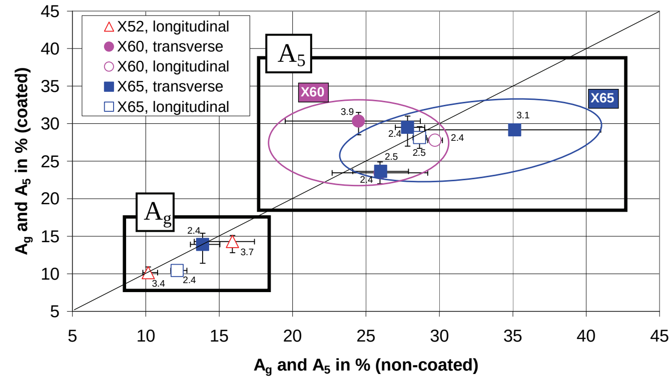

Figure 11: Comparison of A_g and A_5 between non-coated and coated pipe as a function of the material grade and specimen orientation

MULTIAXIAL LOAD CASE: PRESSURE PLUS BENDING

Strain-based design mainly focuses on prevention of damages produced by high longitudinal strains. As the majority of displacements cause a bending deformation of the pipeline (curvature), the two different failure modes tensile rupture and compressive buckling have to be met. Especially thin-walled pipes (high *OD*/*t*-ratios) show an enlarged risk for stability failures (buckling) when exposed to bending. The strain-based design criterion aims at maximum strain value ε_v below the critical strain $\varepsilon_{critical}$:

$$\varepsilon_V \leq \varepsilon_{critical} \tag{1}$$

ε_v includes the plastic equivalent strain and thus all load effects as internal pressure p_i, external forces, stress-strain-state in the cross-section of the pipe wall and the strain-hardening characteristic. The critical strain $\varepsilon_{critical}$ represents the pipe resistance and is a function of geometry, mechanical properties and possible material imperfections.
A plastic deformation together with strain hardening of the pipe material precedes pipe failure. In order to provide sufficient plastic reserves for strain-based design applications, several material parameters are relevant. In case of tension, especially for bending loads, pipelines are required to have low yield-to-tensile ratios (*Y/T*), high strain hardening rates (n_H) and high uniform elongation (A_g) [Zheng et al., 2012; Rivinius et al., 2012; Igi and Suzuki, 2007; Suzuki and Igi, 2007]. Additionally high yield and tensile strength increase the load capacity concerning bending, axial forces and internal pressure. The actual influence of characteristic material parameters on the buckling behaviour are discussed in several mathematical models, summarized in [Karbasian et al., 2012]. Generally the critical strain $\varepsilon_{critical}$ is increased with higher internal pressure p_i, reduced *Y/t*-ratio and lower *OD/t*-ratio. The influence of mechanical properties like yield strength is discussed controversially. In order to calculate the critical bending radius or critical bending moment the strain hardening exponent n_H must be implemented in suitable modelling concepts to assess the structural pipe performance in terms of critical plastic strains.

An analytic model based on von Mises yield theory using isotropic hardening material was developed. In the following an example is given demonstrating the influence of specific material parameters on the pipe bending capacity.

Analytic modelling of multiaxial strain states

The general format of the assessment procedure was already published in [Höhler et al., 2009; Höhler and Brauer, 2011]. Basically, the von Mises yield criterion is applied, where the strain hardening behaviour is inserted as a function. The stress-strain results derived from uniaxial tensile or compression tests are considered, starting from yield strength and ending at tensile strength by reaching the uniform elongation. In case of compression test the stress-strain results between 0.2 % and 3.0 % plastic strains are used. The curve in this region is approximated by a function of the plastic strains $k(\varepsilon_v^p)$. A power function following Hollomon power law [Hollomon, 1949] represents the curve's shape in a realistic manner:

$$k(\varepsilon_v{}^p) = C \cdot \left(\varepsilon_v{}^p\right)^{n_H} \tag{2}$$

In (Eq. 2) n_H is the Hollomon strain hardening exponent and C_H is a material constant.

In case of bending moment both tensile and compressive strains develop in the pipe section. Then additional stability mechanisms, such as buckling, may dominate structural pipe behaviour. Literature and codes provide a variety of formulae to determine buckling loads or critical compressive strains. Comparing different theoretical modelling approaches it was shown, that the DNV-OS-F101 [DNV-OS-F101] provides a suitable assessment of buckling strains for line pipe when exposed to axial forces, bending moment and internal pressure [Karbasian et al., 2012].

Example: Pipe X65, OD = 406 mm, t = 9.5 mm

The estimation of bending moment and strains is carried out for an example pipe section (outer diameter 406 mm, wall thickness 9.5 mm) of steel grade X65. Internal pressure is kept constant at 60 % p_{SMYS}. The material behaviour was attained by tensile and compressive tests on specimens extracted in longitudinal pipe direction, because for bending loads the axial direction is the decisive loading direction. Two pipe conditions are compared, the "as rolled" pipe on the one hand and the "thermally aged" condition due to the coating process, on the other hand. The analytical calculation was carried out twice for each condition, namely

1. for the tensile zone of pipe section, using tensile test material data,
2. for the compressive zone, with compressive test material data, gained from the opposite cross-section fibre.

The material data used is listed in **Table 2**.

Table 2: Material data, tensile and compression tests (longitudinal)

Condition and test	$R_{t0.5}$, $\sigma_{d0.5}$ in MPa	R_m, $\sigma_{d3.0}$ in MPa	Y/T, $\sigma_{d0.5}/\sigma_{d3.0}$	A_g in %
AR compress.	527	612	0.86	-
AR tensile	519	603	0.86	12.1
PE compress.	453	605	0.74	-
PE tensile	495	595	0.83	10.4

"AR" = as rolled, "PE" = PE-coated (thermally aged)

Figure 12 shows the load-strain evolution for the tensile zone. If buckling would not play a role, tensile tearing would be expected at the moment where uniform elongation (A_g) is reached. The diagram for the compressive pipe section in **Figure 13** contains additionally the critical buckling states (circles). Evidently, for this example, buckling is expected before tensile tearing of the pipe wall will take place, as the limit compressive strains are smaller than the material's uniform elongation.

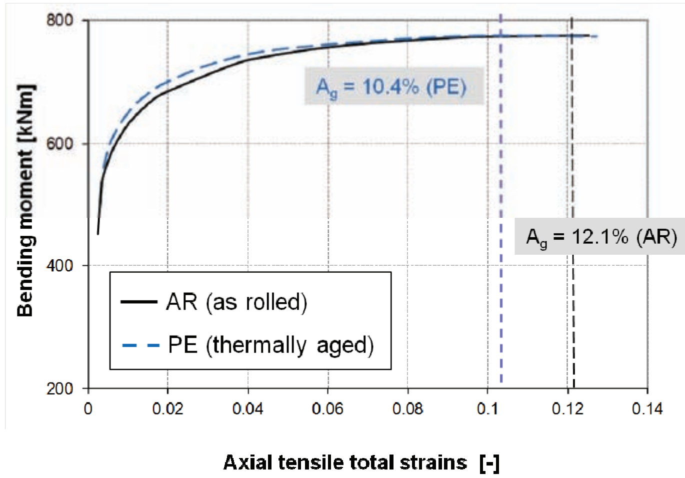

Figure 12: Bending moment – strain evolution for the tensile zone

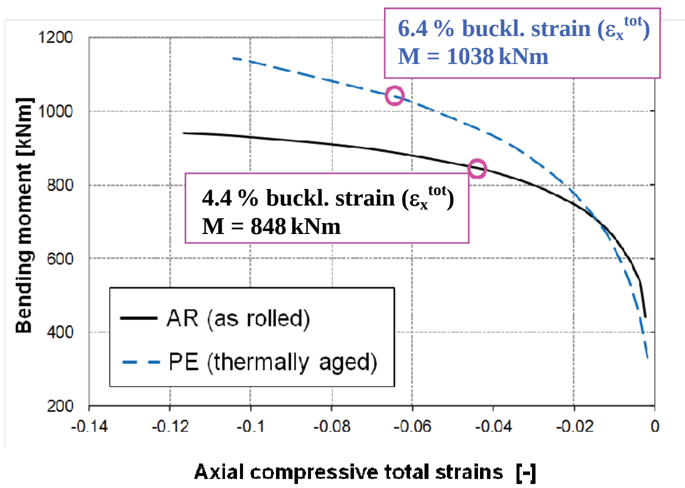

Figure 13: Bending moment – strain evolution for the compression zone

The figures reveal the influence of the material parameters: as Y/T is significantly lower compared to the as-rolled condition, the PE coated pipe provides a more favourable buckling behaviour, with higher critical strains and buckling moment. This is in agreement with investigations of other authors [e.g. Shitamoto et al., 2012]. Yet, the PE coated pipe shows a greater variation of tensile and compressive data, and for the tensile zone the strain capacity is slightly reduced. In both examples, the anisotropy of longitudinal versus hoop direction is not considered. Nevertheless, in such a multiaxial load case for high pressure loading, the hoop behaviour influences the pipe performance considerably. Thus, next research steps will include the model refinement for anisotropic behaviour.

CONCLUSIONS AND OUTLOOK

Extensive mechanical tests of HFI-welded pipes in grades X52 to X65 have been carried out to determine the anisotropy and the strain-aging resistance. Therefore specimens taken longitudinally and transversely to the pipe axis out of non-coated and PE-coated pipes have been investigated in tensile and compressions tests. Anisotropy is generated mainly for the yield strength by the pipe forming process. The $R_{t0.5}$ values are higher in longitudinal pipe direction than for the transverse direction. As expected a reverse behaviour was found for the compressive yield strength $\sigma_{d0.5}$. The coating process tends to lower $\sigma_{d0.5}$ more severely than it raises the tensile yield strength. Therefore the compression yield-to-tensile ratio is decreased more than the tensile *Y/T* when the pipe material is exposed to typical coating temperatures.

The determined characteristic material properties have been used to compare the strain-based design behaviour of non-coated and PE-coated HFI-pipes with the developed analytic model including isotropic hardening. The PE coated pipe provides a more favourable buckling behaviour, with higher critical strains and buckling moment, as *Y/T* is significantly lower compared to the as-rolled condition.

Aim of further investigations is on one hand to include anisotropy into the analytic model. On the other hand additional full-scale tests on HFI-pipes with respect to the strain-based design behaviour under combined internal pressure and bending loads will be carried out and compared with the analytic model. For the full-scale tests the newly installed test equipment of the Salzgitter Mannesmann Research Centre (Duisburg, Germany) will be used (see also paper 2013-TPC-0755). Full-scale tests are necessary to validate analytical models, as the use of material test specimens out of pipes often leads to a prediction of structural behaviour not as accurately as needed [Brauer et al., 2007].

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