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IMPACT OF SMALL-SCALE REELING SIMULATION ON MECHANICAL PROPERTIES ON LINE PIPE STEEL

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ABSTRACT

Reel-laying is a fast and cost effective method to install pipelines since the time consuming operations of welding and inspection are conducted onshore. During reel-laying repeated plastic strain is introduced into a pipeline which may affect strength and ductility of the line pipe material. Based on the experience, it has been shown that the small-scale reeling test procedure according to DNV-OS-F101 [1] is a good way to inspect the mechanical properties for the reel-laying process. Coupons from pipes are loaded in tension and compression tests and aged if required. Specimens for mechanical testing are machined from these coupons and tested according to the corresponding standards.

This paper demonstrates current efforts to demonstrate the usability of cold-formed HFI pipes from Salzgitter Mannesmann Line Pipe GmbH (MLP) for the reel-laying process. In a first step the results of the pre-strained materials are compared in extensive material tests with the undeformed incoming materials. The effect of thermal aging from the coating process on the reeling behavior is then examined, in relation to the background of thermal aging. In discussing the difference between compression and tension zone of the reeled pipe, the influence according to the load conditions is analyzed by the material property tests. This paper demonstrates current efforts of the availability for use of cold-formed HFI pipes for the real-laying process. In addition, the report notes the difference and the effects of the material properties to testing according to the strain-based or stress-based load conditions. In discussing the influence of the tempered conditions of the mechanical properties, therefore two different pipe conditions are investigated by the small scale-reeling (SSR) testing procedure. In summary the results of the pre-strain materials are comparable with the unformed incoming materials.

INTRODUCTION

Offshore pipeline installation can be performed by “J-laying”, “S-laying” and “Reel-laying”. Typically, the first two methods refer to lay barges having welding stations on-board with which the individual pipes are joined whereas in the latter case process the pipeline is welded onshore. Each one of these methods has its advantages and limitations. Typically, laying of pipelines in shallow and intermediate water is performed using the S-lay process whereas the J-lay process is less suited for shallow water. The production rate and speed of both methods can differ significantly whereas both of them expose the pipeline to a relatively small amount of plastic deformation [2]. Hence no special attention has to be paid to possible changes of material properties induced by the laying process that could impact the operating condition of the line. Concerning the pipe geometry, there are no significant limitations coming from the process.

In contrast to this, the reel-laying process (Figure 1) is suitable only for smaller diameter pipes. Currently, the largest diameter of a rigid pipe suitable for this installation method is around 16-18”. The process is a cost efficient alternative as the welding that is the most time consuming process on lay barges is conducted onshore and the reel barges merely install the welded line. Reel-laying can be performed from shallow to ultra deep water. The process of reeling on and off the reel drum does lead to significant plastic deformation of both pipes and circumferential welds that has to be accounted for in the design. In particular, material properties after plastic deformation have to be determined and assessed with respect to the underlying requirements.

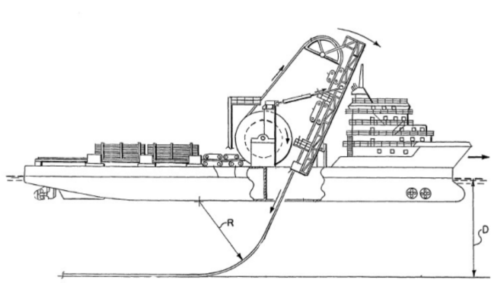

Figure 1: Reel-laying (schematic)

DNV-OS-F101 [1], one of the major offshore standards, suggests two methods to simulate the cyclic deformations the pipes are exposed to during reel-laying. The pre-straining can be carried out as full-scale bending of whole pipes sections, called full-scale reeling (FSR), or as tension/compression straining of material cut from the pipe wall (segment specimens), known as small-scale reeling (SSR). After straining the samples are artificially aged at 250 °C as it is specified in DNV OS F101 for one hour before the mechanical testing can be performed. A scope of the test scheme of reeling simulation is given in Figure 2.

In the following the effect of heat treatment and SSR regarding to mechanical properties is described. More about FSR and the comparison between SSR and FSR can be referred in [3].

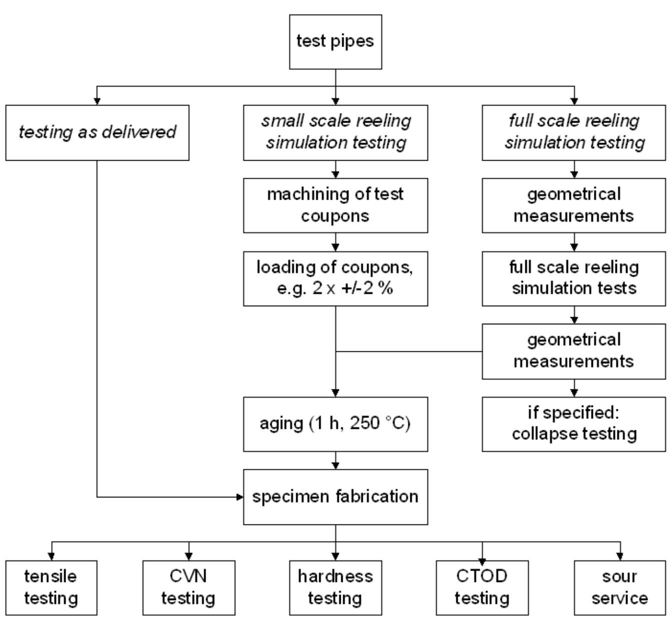

Figure 2: Test scheme of reeling simulation

General – small-scale reeling

Reeling simulation on a laboratory scale (SSR) is performed in accordance with DNV-OS-F101, requirement P, unless otherwise specified by the customers.

Within the named sections, there are limits defining when such procedure becomes mandatory. This is the case if any single operation leads to plastic strain exceeding 1 % or if the accumulated plastic strain exceeds 2 %. Typically, two to three strain loops consisting of single cycles of strains in the range of 1.5 % and 3 % are required. The cycles are chosen such that they are suited to simulate the actual reeling installation process that typically consists of reeling on, reeling off, aligning and straightening.

The maximum strain in each cycle is closely related to the pipe and vessel dimensions, in the latter case most importantly the reel drum. As the pipe is reeled onto and off the drum the fibers in 12 (extrados with respect to the drum) and 6 (intrados) o'clock position are exposed to cycles ending in both compression and tension, respectively. As these differences in strain history may have a major influence on material properties, it is recommended to simulate both in SSR in order to have a complete picture of the structure as it enters operational stage.

According to Section 7 (I300) and Appendix B (B1102-1110) of DNV-OS-F101 reeling shall be performed on samples (longitudinal coupons) removed from the finished pipe. The coupons should be of full wall thickness, if the compression and tensile testing device has sufficient capacity, in order to give the best representation of the product that is simulated and thus give the most reliable prediction of the structural response. In order to apply compressive loads without causing buckling of the test section, DNV-RP-F108 proposes for typical pipe geometries being used in reeling applications (OD 11”-12” and wall thickness around 15-25 mm), a length of the coupon which does not exceed 50 mm [4]. The widths of the specimens are selected individually according to the final mechanical tests. Straining of the specimens is normally performed with a servo-hydraulic testing machine in uniaxial tension and compression. Figure 3 shows different coupons (dark, large specimens) depending on the subsequent mechanical tests and, for better illustration, the test specimens that are extracted from the coupons after reeling, which are the lighter and smaller ones in the picture.

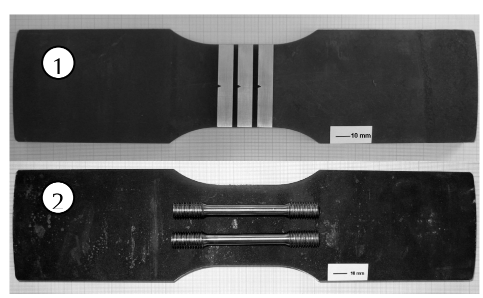

Figure 3: Example for SSR coupons and following test specimens

Plastic deformation
During production of pipes, pipe laying and in service, pipeline steels can be subjected to external and internal mechanical as well as thermal loads. Since these loads affect steel properties, it is necessary to know about the impact and consequences on the material properties.
Three major effects can be observed when repeated plastic deformation is introduced into a pipe. These are
- strain hardening,
- Bauschinger-Effect,
- strain aging.
Alongside changes in strength, toughness and ductility are usually influenced, too.

Strain hardening
The effect of strain hardening can be observed in ductile metals in which the yield strength is elevated after plastic deformation at temperatures below crystallization temperature. Figure 4 shows schematically the procedure of the strain hardening effect. The point σ_1 represents the elastic limit of the material. Up to this point, the initial elastic region generally appears as a straight line (Hooke´s law). Above the elastic limit, the response of the material is both elastic and plastic. If a specimen is loaded continuously to a value $\sigma_2$beyond the initial elastic limit in the first time and then completely unloaded, the load drop follows an almost elastic unloading which is parallel to the initial linear region of the curve. But, after unloading the strain is not zero. This remaining portion of strain is referred to as plastic strain. If this specimen is reloaded, the stress-strain curve follows a reloading path identical to the unloading path, as long as the strain is small. Deviation from linearity takes place as soon as the original curve is reached again (σ_2). Naturally, this occurs at a higher load, indicating that elastic limit has increased. This phenomenon is related to elastic limit, ultimate tensile strength (UTS) remains unaffected. Consequentially, yield to tensile ratio (Y/T) increases, indicating reduction of ductility which is very important e.g. for pipelines designed for strain-based design [5].

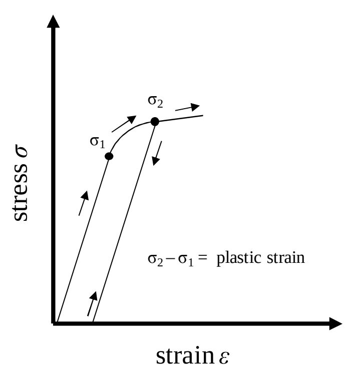

Figure 4: Strain Hardening Effect

Bauschinger effect
During reel-laying, the pipe is loaded not only unidirectional but repeatedly loaded and re-loaded in reverse direction, beyond σ_b the initial yield point σ_a. This type of loading is frequently associated with the Bauschinger effect which is linked to the observation that, after initial plastic deformation, the yield strength σ_c in reverse direction is lower than the initial one (Figure 5) [6].
The phenomenon of Bauschinger effect can be attributed on residual stresses of 2nd and 3rd type [7].
Additionally, as pointed out for strain hardening, ductility and toughness may be affected.

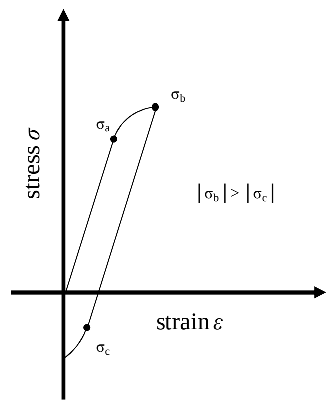

Figure 5: Bauschinger Effect

Strain aging
The terminology strain aging is associated to cold deformation of a steel followed by exposure to elevated temperatures, where elevated can be any temperature above ambient in conjunction with a sufficient time of exposure [8]. In this case, not only yield strength σ_1 vs. σ_2 is affected as in the case of strain hardening but, at the same time, UTS is expected to rise, too. Figure 6 illustrates the increase in the strength for low carbon steel.
Strain aging can be controlled by lowering the amount of carbon and nitrogen in solution.

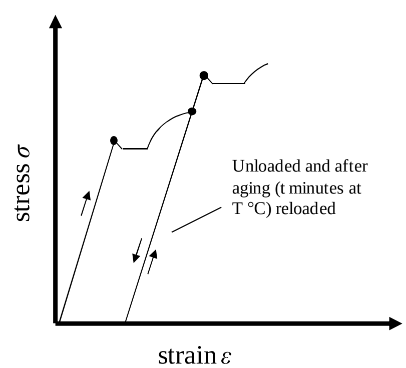

Figure 6: Strain Aging

Small-scale reeling simulation tests

An overview of the testing program that is presented in the following is given in Figure 7.

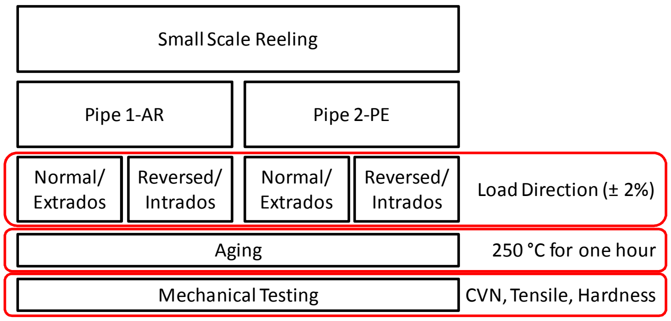

Figure 7: Test Program

The testing program was conducted on HFI pipes of API 5L [9] grade X65M with an outside diameter of 323.9 mm and a wall thickness of 15.9 mm. The investigation included two pipe conditions as-rolled and aged to include any thermal aging effect from Polymer coating process. In the following the pipes are referred to as:

- Pipe 1 – AR ("as rolled")
- Pipe 2 – PE ("PE-coated")

The reeling simulation consisted of experimentally investigating both loading paths ending in compression load (normal, extrados) and in tension load (reversed, intrados). The denotation "normal" refers to the fiber of the pipe on the reel drum that, in this case, is the extrados subjected to tensile loads in the reeling on cycle. Denotation "reversed" refers to the intrados of the pipe that is on the reel drum, that is then subjected to compressive strains. In total four combinations of pipe and straining condition are presented in this paper.

According to DNV-OS-F101 and typical specification requirements, the small-scale testing procedure includes: plastic deformation of two cycles in normal and reverse configuration, each cycle consisting of 2 % strain in tension and compression in the orders described before, thermal aging (250 °C/ 1 h) and mechanical testing. Figure 8 shows the stress-strain path of the coupons extracted from the pipes in both loading conditions. The Bauschinger effect can be observed after applying the first plastic load (tension or compression). In both cases of normal and reverse load path there is a significant drop in YS in the opposite load direction.
The YS upon reloading in initial directions in slightly decreased with respect to the initial YS, too. Towards higher amounts of plastic strain, the two curves tend to follow the same path again. This reflects the fact that the Bauschinger effect affects YS rather than UTS.

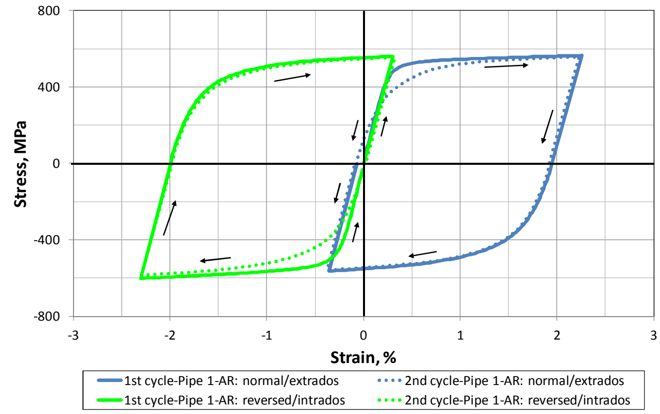

Figure 8: Normal and reversed hysteresis

After having reeled the coupons and exposed them to a thermal aging procedure of 250 °C at 1 hour, the mechanical properties in terms of tensile, Charpy impact and hardness tests were determined.

Results of mechanical testing and discussion

The mechanical characterization consists of round bar tensile-, Charpy impact- and Vickers hardness test. The results are described below.

Tensile properties

Tensile tests were conducted on round bar specimens extracted in longitudinal direction according to DIN EN ISO 6892-1. Figure 9 shows a comparison between normal and reversed reeling mode of both pipe conditions (as-rolled, thermally aged). "as-delivered" represents the results of the as-delivered pipe before SSR simulation and thermal aging. A solid point and an open point represent the result of "normal" reeling simulation (extrados) and "reversed" reeling simulation (intrados), respectively. In case of as-delivered condition, although UTS hardly change, YS increase by around 15 MPa by thermal aging. Significant differences can be observed in the YS values ($R_{t0.5}$) in dependence of the loading path. YS after reeling simulation ending in compression load (normal, extrados) is affected by the Bauschinger and thermal aging effect, thus the YS shows a slight decrease compared to the initial YS. In this case, YS and UTS hardly change. Hence, the increase due to thermal aging is canceled by decrease due to the Bauschinger effect. On the contrary, if the reeling simulation ends in tension load, the properties are affected by the strain hardening and thermal aging effect. In this case, YS values increase up to 15 % in respect to the initial conditions. Therefore, YS to UTS (Y/T) increase .Effectively this means that the strength properties of the pipe after having been exposed to reeling loads, i.e., reverse plastic deformation, depend only on the direction of the last load cycle.

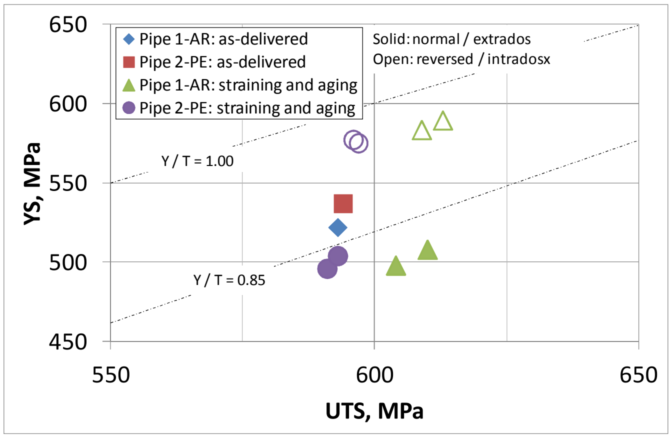

Figure 9: Tensile Values

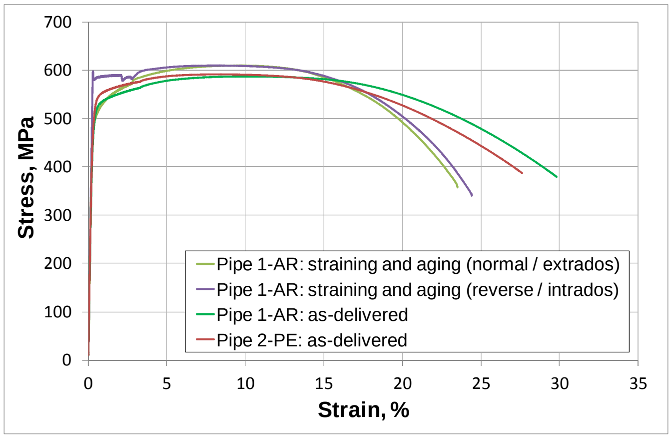

Figure 11: Stress-strain curves from tensile tests before and after reeling simulation

Figure 10 shows stress-strain curves of material after exposure to reeling and aging. After reversed reeling simulation, the stress-strain curves show a discontinuous shape with a pronounced yield point and subsequent Lüders bands. This behavior cannot be observed in the tensile test after normal reeling; here the curves have a round house shape. Consequently, the yield to tensile ratio Y/T after reversed reeling simulation is higher than after normal reeling simulation. The comparison of the tensile tests after reeling simulation to material before reeling is given in Figure 11. The curves of Pipe 1-AR and Pipe 2-PE have a round house shape before strain and thermal aging. The yield points (Lüders band) are present or absent after strain aging according to the direction of straining. The Lüders band is present, if the sample is strained in the same direction as the last loading sequence during reeling simulation before aging. If the sample is strained in the direction opposite of that before aging, the Lüders band is absent and a round house shape is present [10-12].

Toughness properties

Transition curves obtained with Charpy impact tests of two pipes that were exposed to both reeling simulation procedures are depicted in Figure 12. For comparison, the impact energy measured on the as-welded pipes tested at design temperature is included. Typically design temperature of offshore line pipes are in the range of 0 °C up to -20 °C. Taking into account the statistical background, and within the normal scatter, there is no relevant difference in the transition curves representing the different load paths. On the other hand, there is a difference between the transition curves obtained from both pipes. In general, the toughness values measured from the PE aged pipe are slightly lower than those of the as-rolled pipe. In comparison to the impact energy measured in the as-welded pipe, there is a trend towards lower values. The transition temperature (50 % ductile fracture) is in the range of -40 °C to -30 °C (Figure 13).

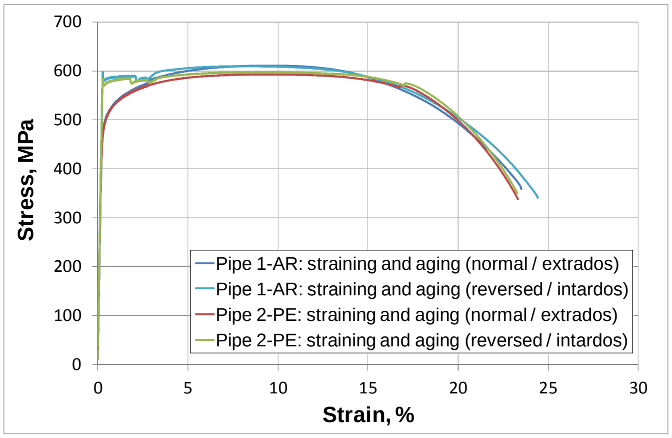

Figure 10: Comparison of tensile stress-strain curves after reeling simulation

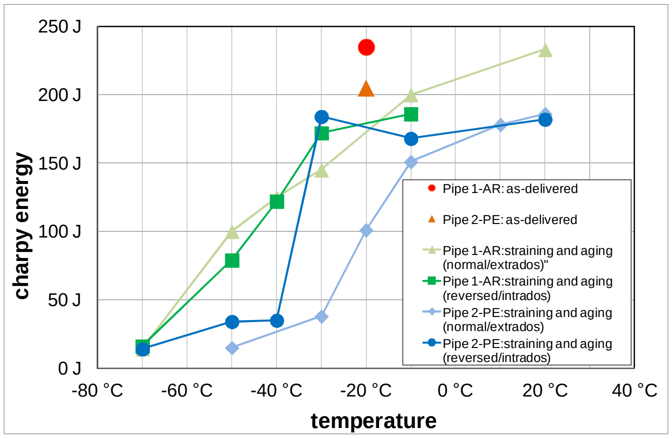

Figure 12: Charpy energy as a function of test temperature, loading path and heat treatment

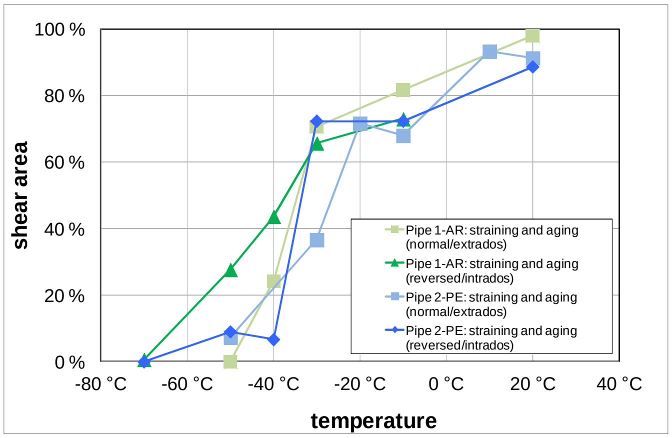

Figure 13: Charpy impact test – shear area vs. temperature

Hardness properties

A significant difference can be observed between the values of the position along the wall thickness (Figure 13). The hardness of the pipe is higher on the inside than on the outside of the wall thickness, which may be a consequence of the coil production process. Apart from that, significant influence of the loading path cannot be observed by the hardness values.

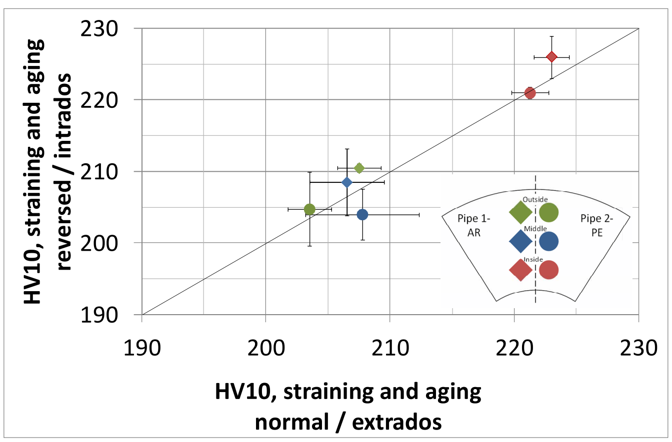

Figure 13: Vickers Hardness (HV10)

Conclusions

The reeling behavior of a high-frequency-induction (HFI) welded pipe was investigated via small-scale reeling (SSR) simulation and following mechanical characterizations. Together with the two load cycle directions (normal, reserved) during the reeling simulation and the two initial pipe conditions (Pipe 1-AR and Pipe 2-PE), four different conditions have been evaluated in total.

The test procedure was carried out according to the standard DNV-OS-F101 and typical client's requirements.

The investigation showed that the tensile properties depend on the last load cycle. The yield points (Lüders band) are present or absent after strain aging according to the direction of straining. By contrast, the toughness properties are not significant affected by the last load cycle before thermal aging. Toughness properties decrease with respect to the strain and thermal aging. Analog to the impact of toughness properties by SSR, the hardness properties will not be influenced by the last load path.

Comparison to full-scale reeling investigation is given in IPC2014-33163-Full-Scale Reeling Tests of HFI Welded Line Pipe for Offshore Reel-Laying Installation.

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