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ANALYSIS OF ANISOTROPIC HARDENING IN HIGH STRENGTH STEEL (HSS) IN LINE PIPES FOR STRAIN-BASED APPLICATIONS

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In this paper are reported the results of an extensive and innovative mechanical characterization carried out on three large diameter line pipes for gas transportation useful to calibrate a new plasticity finite element numerical simulation (FEM) model developed at Rina Consulting – Centro Sviluppo Materiali. In particular, the anisotropic hardening for the materials has been characterized by tensile tests carried out in the base material of the pipe with tensile specimen extracted along different orientations, considering also the pipe through thickness direction.

Key words: HSS, pipe, anisotropy; mechanical properties; large strain

INTRODUCTION

Oil and gas transmission pipeline steels with high deformation capability are required for environments (earthquake zones, permafrost zones, forest heave, deep sea applications, etc.) where large strata movement may occur. When large strata movement occurs the pipeline is exposed to large plastic deformations that can result in failure. Pipelines operating in these environmental conditions utilize a strain-based design strategy to protect the pipeline from failure. This strain-based design strategy for transmission pipelines requires that the pipe must not only have the capability to withstand the high internal operating pressure but must also have good deformation resistance characteristics. Therefore, pipeline steels with high deformation capability supplied to strain-based application have to achieve high strength/toughness, good welding performance together with excellent plastic deformation ability. This requires that the pipeline steel's transverse performance must meet the pipeline steel grade technical specification requirements of strength, toughness, drop weight tear test, hardness etc.

In addition to the transverse mechanical property requirements, pipeline steel for these applications must also meet longitudinal requirements. A higher degree of deformation-enhanced index (n), larger uniform elongation (A_g, %), low yield to tensile ratio ($R_{t0.5}$ /R_m), continuous yielding (roundhouse) tensile stress-strain curve with no yield point elongation are required to achieve good longitudinal deformation ability. The development of high strength line pipe material for strain-based design applications has been driven forward successfully in the recent years [1-4]. Also the design methods and prediction tools have improved continuously [5]. For the plate material development, the understanding and the control of the microstructure are the key to success. Besides the chemical composition, the cooling process has the most significant influence on the formation of microstructure [6-9]. Minor differences in cooling conditions can strongly affect the mechanical properties such as uniform elongation and $R_{t0,5}$ /R_m [10].

It is well known that mechanical properties of line pipes could be strongly different along the pipe principal axes [11]. Anisotropic or orthotropic material properties have an important influence on the pipeline performances, and large straining beyond the plastic instability limit (necking) needs to be accurately described with a proper anisotropic plasticity constitutive law in order to capture the material ductile behavior. For this purpose, in this paper results are concerning an extensive and innovative mechanical characterization carried out on three large diameter line pipes for gas transportation useful to calibrate a new plasticity model developed at Rina Consulting – Centro Sviluppo Materiali [12-14]. The aim of this activity is to evaluate the differences of yield stress and subsequent hardening of the materials for differ material orientations.

MATERIALS AND METHODS

The main information of the pipes is reported in Table 1. Both spiral pipes and pipes manufactured by a forming process constituted by U, O and E steps (UOE pipes) are considered.

Table 1 **Materials tested**

Material Grade	Pipe outer diameter / in	Pipe wall thickness / mm	Pipe manufacturing process
API X70	56	22,3	UOE
API X80	48	19,8	UOE
API X70	48	19,3	Spiral

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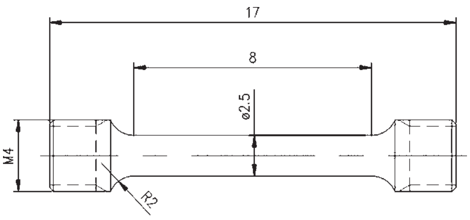
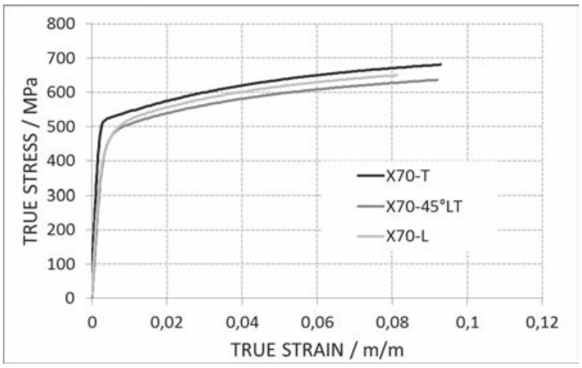


Figure 1 Mini round tensile specimen

The material anisotropy was characterized by tensile tests carried out in the base material of the pipe with tensile specimen extracted in six different orientations. Three standard tensile test, with geometry according to UNI EN ISO 6892-1:2009 are carried out on round bar smooth specimen having 9 mm gauge section diameter, extracted in the longitudinal (L), transversal (T) and 45 ° degrees between L-T directions (45 °LT) of the pipe. Three tensile tests are carried out on round specimen having 2,5 mm gauge section diameter (Figure 1), extracted in the through thickness direction of the pipe (N), and oriented at 45 ° degrees from longitudinal and trough thickness direction (45°LN) and at 45° degrees from transversal and trough thickness direction (45 °TN).

The dimensions of the tensile specimens are limited by the wall thickness of the pipe from which the specimen are extracted. Only for the spiral pipe additional tests are carried out on round bar smooth specimen having 9 mm gauge section diameter, extracted in the longitudinal (L), transversal (T) and 45° degrees between L-T directions (45 °LT) of the coil forming the pipe.



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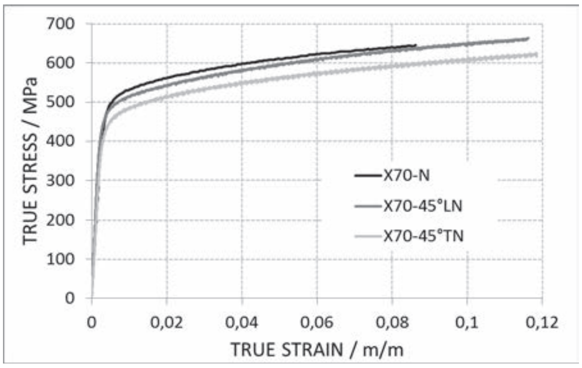

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Figure 2 X70 True stress-strain curves derived from tensile tests on 56" OD UOE Pipe. a) 9 mm OD round bar test; b) 2,5 mm OD round bar test

EXPERIMENTAL RESULTS

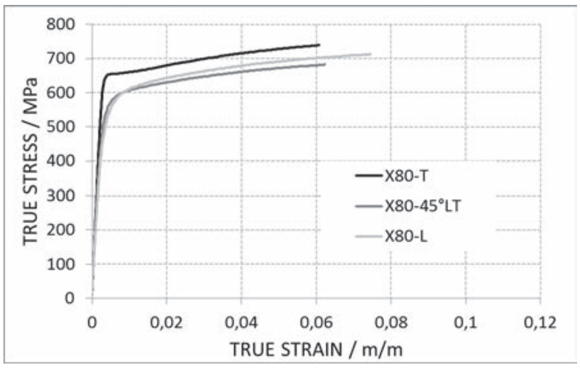
Results of the tensile test are reported in terms of true stress-strain curves for the strain up to specimen necking. For each pipe the curves obtained from standard tensile test, carried out on in plane pipe directions, are separated from those obtained from mini round specimen obtained in trough thickness directions. Results are summarized from Figures 2 to 5. Only for the spiral pipe further tensile test has been performed in the direction of longitudinal coil orientation, transversal coil orientation and 45° between longitudinal and transversal coil orientation (Figure 5).

Considering a spiral pipe forming angle of about 25°, for the spiral pipe 6 different orientations for the in plane tensile test are considered (Table 2).

Table 2 **Orientation for tensile tests on X70 48" OD Spiral Pipe**

Orientation ID	Orientation direction / °
Longitudinal Pipe	0 and 180
Transversal Coil	25 and 205
45°LT Coil	70 and 250
Transversal Pipe	90 and 270
Longitudinal Coil	115 and 295
45° LT Pipe	135 and 315

The yield stress at different orientation are reported in subsequent Figure 6.



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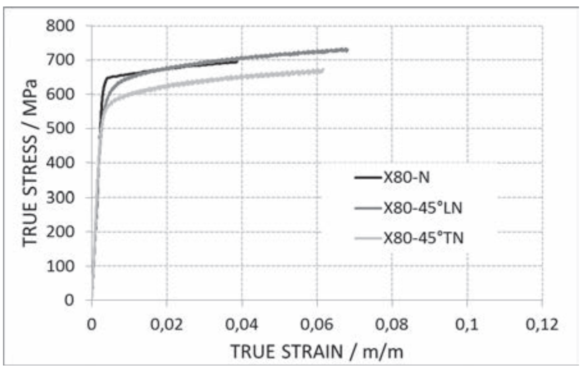

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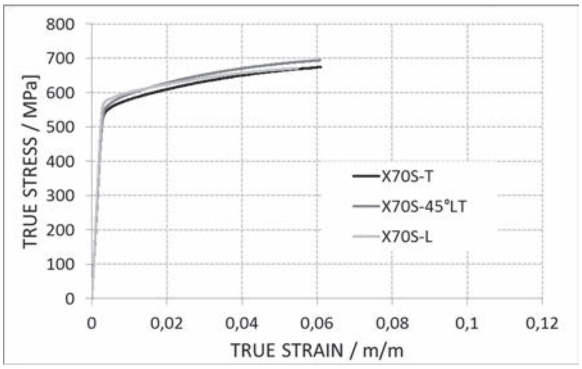
Figure 3 X80 True stress-strain curves derived from tensile tests on 48" OD UOE Pipe. a) 9 mm OD round bar test; b) 2,5 mm OD round bar test



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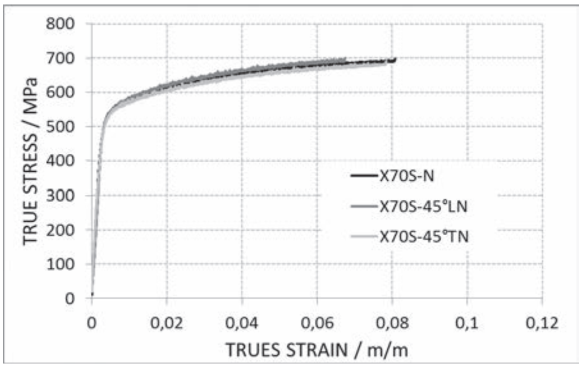

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Figure 4 X70 True stress-strain curves derived from tensile tests on 48" OD Spiral Pipe. a) 9 mm OD round bar test; b) 2,5 mm OD round bar test

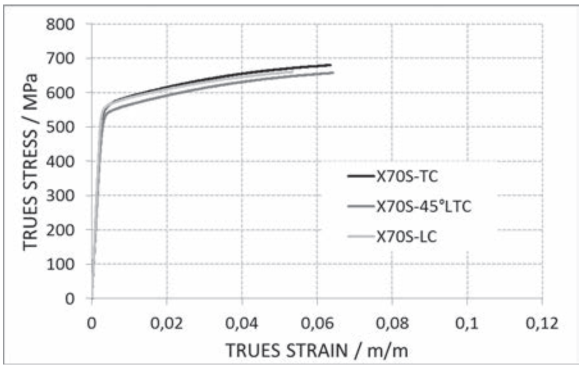

Figure 5 X70 True stress-strain curves derived from tensile tests on 48" OD Spiral Pipe according to coil direction.

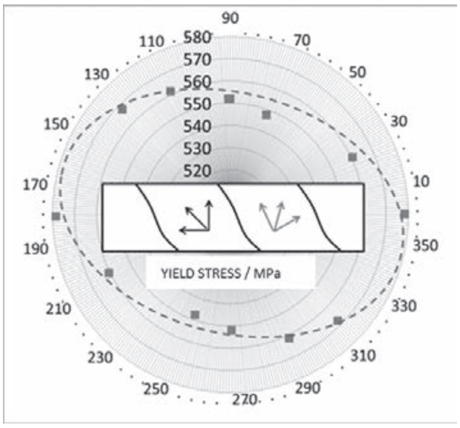

Figure 6 X70 Yield stress derived from tensile tests on 48" OD Spiral Pipe for different orientation. (Longitudinal pipe direction = 0°)

DISCUSSION

The manufacturing rolling process of plates and coils develops anisotropy in the final product. Following process of UOE and Spiral pipes shaping induce further change in the material behavior.

First result is that the UOE pipes have three principal anisotropic axis oriented along the pipe principal direction, longitudinal, circumferential and through thickness while the spiral pipe has this principal axis rotated as shown in the Figure 6.

For better understand the differences of the material behavior in the three orientations, longitudinal, transversal and radial pipe, for each material the stress-strain curves are normalized according to the results obtained in the pipe transversal direction. (Figures 7 to 9).

Main outcomes obtained from Figures 7 to 9 are:

- UOE pipes shown higher stress values in the pipe circumferential direction than longitudinal.

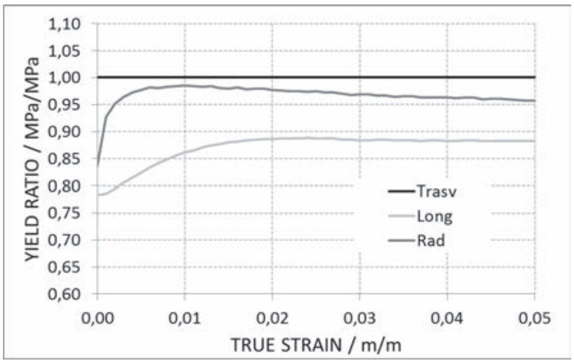

Figure 7 X70 Normalized true stress-strain curves derived from tensile tests on 56" OD UOE Pipe.

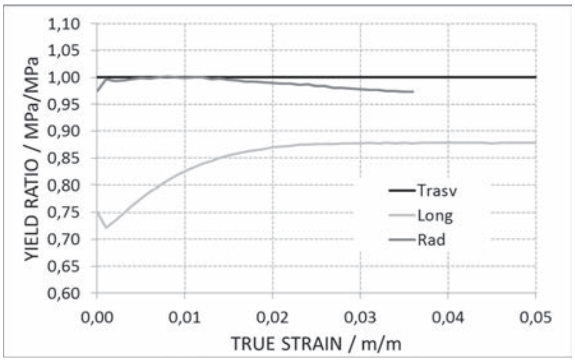

Figure 8 X80 Normalized true stress-strain curves derived from tensile tests on 48" OD UOE Pipe.

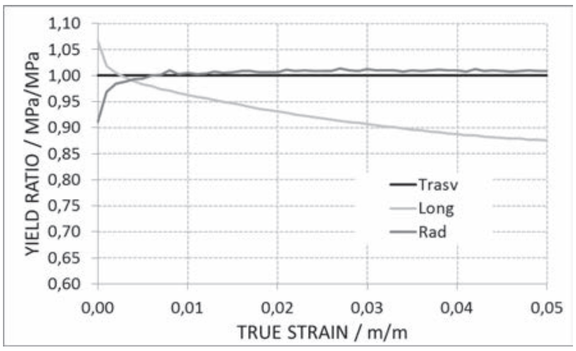

Figure 9 X70 Normalized true stress-strain curves derived from tensile tests on 48" OD Spiral Pipe.

- At lower strain Spiral Pipe, shown higher stress values in the pipe longitudinal direction than circumferential, as opposed to UOE pipe.
- Ratio between stress strain curves evolves with strains, so the anisotropy of the pipes changes during deformation.
- Material behavior in the trough thickness direction is different from longitudinal and transverse direction for all the three pipes.

It is worth nothing that the trough thickness behavior of the material affects the pipe response to biaxial stress state like pipe bending with internal pressure. Pipes with same longitudinal and transversal material properties can have different response to same loadings due to their differences in the material trough thickness behavior.

CONCLUSIONS

The differences existing between the original coil and plate anisotropy and the subsequent different manufacturing process leads to a certain degree of anisotropy in spiral and longitudinal welded pipes.

This anisotropic or orthotropic material properties have an important influence on the pipeline performances. Yield limit in the circumferential direction is important in relation with the loads represented basically by the service internal pressure. Material properties in the other directions also have an influence in the fracture behavior. For instance, the through thickness necking resistance is important in controlling the limit state represented by the material failure in burst and it is a key parameter in governing the ductile fracture initiation and the fracture propagation resistance in pipelines. The longitudinal fracture resistance is instead important in cases when the pipe is subject to extreme overloads in bending, with possible ductile tearing, such as in case of soil movement on buried pipelines during landslides.

Since the rolling direction is no longer parallel to the pipe axis, spiral welded pipes show different anisotropic behavior. As opposed to UOE pipes, the yield stress of spiral welded pipes in the longitudinal direction results to be greater than those transversal to the pipe axis. Also the trend of the stress-strain curve normalized according to the results obtained in the pipe transversal direction show differences summarized below:

- Ratio between Longitudinal and Transversal stress decrease with the increase of strain in the case of spiral pipe, as opposed to UOE pipes.
- Stress strain curve in the radial direction tends to be more similar to transversal curve than the longitudinal for all the three analyzed pipes.

Acknowledgements

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