STRAIN BASED DESIGN CONSIDERATIONS FOR SPIRAL WELDED PIPELINES

K. Van Minnebruggen[1], W. De Waele[1], R. Denys[1], and P. Thibaux[2]

[1] Ghent University, Laboratory Soete, Belgium
[2] OCAS N.V., Technologiepark 935, 9052 Zwijnaarde, Belgium

Abstract Pipelines are constructed in hostile environments where the occurrence of imposed plastic deformations can necessitate a strain based design approach. Under such conditions not only the strength and toughness properties have to be considered; also the strain capacity of pipe and weld metal become crucial. Considering the use of spirally welded linepipe sections, the helical seam weld and anisotropic material properties pose real challenges to pipeline designers. In our work, the tensile strain capacity and defect tolerance of high strength, high toughness spiral pipes will be investigated. This paper briefly discusses the different steps in the spiral pipe manufacturing process and their influence on the mechanical properties of the pipe. The forming angle is a key parameter as it determines (a) the anisotropy in strength and toughness of the pipe steel, and (b) the orientation of possible seam weld defects. Each mechanical operation (forming, expansion) and each thermal operation (welding, coating) will affect local or global strength, toughness and ductility properties of the pipe metal. A thorough material characterization at each process step is needed for a qualitative and quantitative understanding of these effects.

Keywords: Spiral Linepipe; Strain Based Design; Axial Straining Capacity

1   INTRODUCTION

1.1   The spiral pipe

Due to the fast growing demand for energy, fossil fuels are nowadays extracted in more hostile and remote regions [1]. These environments can be prone to permafrost, landslides, ground settlements or even earthquakes. Due to these extreme loading conditions, the pipelines that transport the fuels can be subjected to large deformation beyond the elastic range of steel. Therefore not only the strength and toughness of the pipe and weld metal but also their axial straining capacity becomes crucial [2]. In these cases a strain based design approach should be applied which limits the allowable imposed axial strain of the pipeline [3, 4]. Depending on the specific project conditions, the allowable design strains can be in the order of two to four percent [5].

Taking a closer look at a pipeline, it obviously consists of multiple line pipe sections connected by girth welds. When a global displacement is imposed, it is undesirable that the girth weld regions are plastically deformed. Girth welds are considered critical regions in a pipeline due to the possible presence of weld defects [6, 7]. When the girth welds are sufficiently insensitive to remote strains (i.e. defect tolerant), the line pipe sections should be able to deform beyond the elastic range without failure, thus guaranteeing the structural integrity of the pipeline.

In pipeline projects which require a strain based design approach the line pipe sections are generally manufactured with the UOE-process. In this process first a plate is bend in a U-shape, followed by closing towards an O-shape, after which the longitudinal seam is welded. Finally the pipe is expanded to ensure a sufficient roundness (see Figure 1).
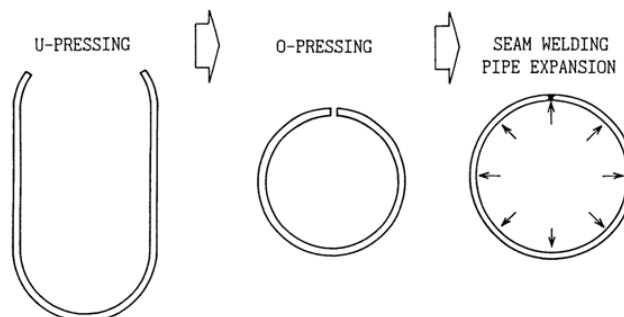

Figure 1: The basic stages of the UOE pipe forming process [8].

An alternative manufacturing process for line pipe sections is the spiral pipe forming process. Here, a skelp is coiled in such a way that a helical or spiral seam occurs. In general this seam is subsequently welded using the submerged arc welding process ('SAW'), (see Figure 2).
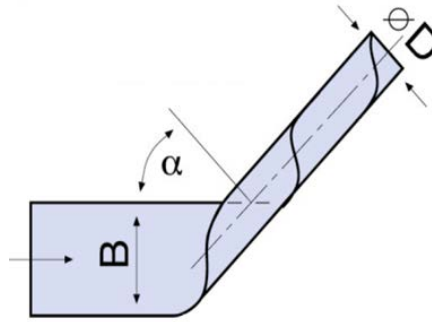

Figure 2: The basic principle of the spiral pipe forming process [9].

Due to economical reasons and the desire to manufacture the pipe close to where it is to be used there is a growing interest for the use of spiral pipes. However, a major scepticism exists concerning their suitability for strain based design related projects. Economical benefits can be obtained due to the more flexible production process and/or reduction of installation cost [10].

A detailed study is necessary to fully evaluate the tensile straining capacity of a spiral welded pipe. This paper gives an overview of the main elements which should be taken into account.

1.2 Industrial use of spiral welded pipelines

Large diameter spiral pipes have been used with success in oil and gas projects for several decades. Pipeline operators are generally positive concerning experience and feedback to the manufacturer. Existing feelings of inferiority of spiral welded pipes compared to UOE are either due to poor manufacturing quality of certain mills (which is also possible for other types of pipes), or they are caused by a lack of operator experience [11].

For use and design of spiral pipelines in allowable stress and/or strain based design projects, other elements apart from tensile strain capacity should be considered. Based on the work of several research groups it can be concluded that in comparison to UOE-pipes, spiral pipes can perform equal or better when considering the following elements: cold field bending [12], buckling resistance [13], fracture arrest [14], ductile tearing [15], and burst fracture tests [16].

A striking example of a spiral welded pipeline in a strain based design project is the second West-East China Pipeline Project (WEPP II). With its total length of 8704 km and travelling through 15 provinces, it is the longest natural gas pipeline in the world. The WEPP II is estimated to cost $22 billion for an annual capacity of 30 billion cubic meters and a minimum lifespan of 30 years. The line pipes have been built using API-5L X80 grade steel with 1219 mm outer diameter and 18.4 mm wall thickness [17, 18].

2 SPIRAL PIPE FORMING

2.1 Skelp production

Pipelines for oil and gas transportation are generally produced using high grade steels, API-5L X60 and beyond, because of their high yield strength [19]. Due to the higher yield strength, pipelines can withstand larger internal pressure, transport larger quantities and increase diameter, while reducing the wall thickness and thus the weight of the line pipe sections. The cost reduction of a pipe due to its weight reduction, dominates over the cost increase of higher grade steels [20-22].

To obtain a high grade steel with an adequate weldability and toughness, the steel is produced using thermo-mechanical controlled processing ('TMCP'). TMCP inherently introduces anisotropic material properties in the steel skelp. This anisotropic behaviour is shown in the yield strength, the toughness and the ductility [23]. The mechanical properties thus depend on the orientation of loading relative to the rolling direction. The highest yield strength is expected in the transverse to rolling direction. The highest ductility and toughness are expected in the longitudinal to rolling direction [24-26]. However the opposite directions do not necessarily provide the lowest values, neither can it be assumed that there exists a linear function between angular position and the magnitude of yield strength, ductility or toughness. The value at each angular position is dependent on the specific production process parameters (e.g. cooling rate, coiling temperature, slab reheating temperature, etc.) [23, 27].

The lowest yield strength can generally be observed in the 30 degrees orientation to the rolling direction. The yield anisotropy (transverse to pipe axis ('TPA') versus 30 degrees) can be up to 100 MPa in API X70 grade line pipe steels. It is generally accepted that grain shape and texture are responsible for this anisotropy in yield strength, and that employing higher slab reheating temperature and/or finish rolling temperature can reduce the yield strength anisotropy [28].

2.2 Pipe forming and welding

The pipe forming can be a continuous process or by two step manufacturing (see Figure 3). The two step manufacturing process separates the pipe forming with tack welding (step one) from the inner and outer seam submerged arc welding (step two) [9]. By separating the final welding into multiple stations, the production speed can be increased up to the forming and tack welding speed. Based on Figure 2, a relationship between the feed skelp width B, the forming angle α and the final average diameter D of the pipe can be established, Eq. 1, (see Figure 4).
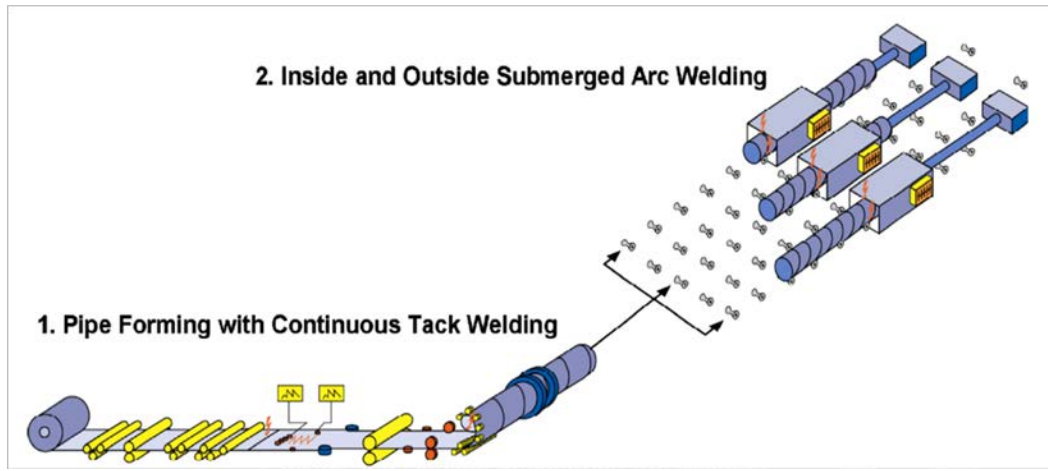
$$D = \frac{B}{\pi \cdot \sin(\alpha)}$$

(1)

Figure 3: Two step spiral pipe manufacturing process [9].

The commercial production range is limited to diameters up to 1500 mm, wall thickness up to 25 mm and the forming angle ranges from 15 to 50 degrees [29]. Pipes can be formed with narrow geometrical tolerances and very high roundness accuracy without cold expansion being necessary [30]. Pipes with steel grades up to X80 are commercially available, and spiral pipes with grade X100 have already been produced in small quantities for specific projects [31].
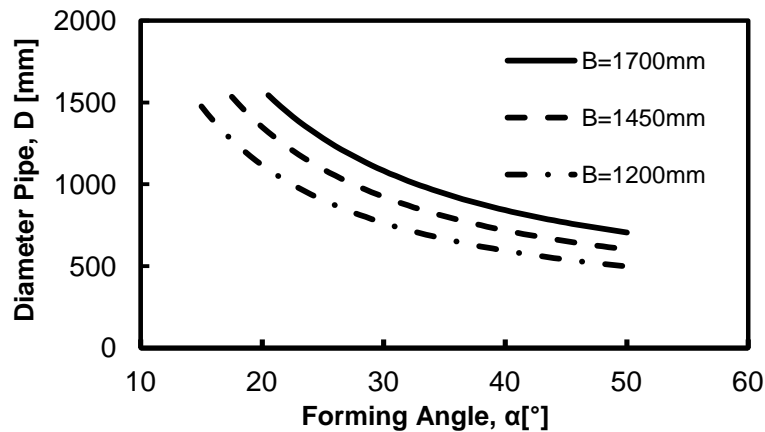

Figure 4: Relationship between diameter and forming angle for different skelp width values.

3 SPIRAL PIPE TESTING

3.1 Mechanical anisotropy

As discussed in section two, a considerable amount of mechanical anisotropy is inherent to the steel manufacturing process. When the pipe is formed, the anisotropic directions obtain a certain orientation with respect to the pipe axis, which is related to the forming angle. Equivalent directions can be found on the skelp corresponding to the transverse to pipe axis (TPA) and the longitudinal to pipe axis (LPA) directions. These are respectively the transverse to pipe axis equivalent (TPAeq) and the longitudinal to pipe axis equivalent (LPAeq) [31]. (See Figure 5).
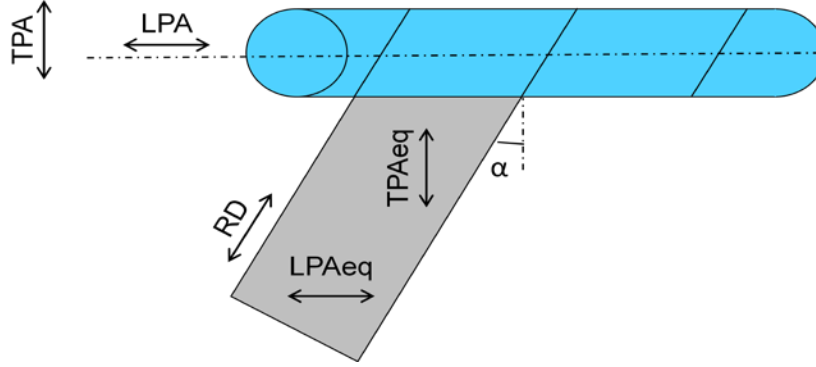

Figure 5: The relationship between skelp rolling direction and pipe longitudinal and transversal directions.

Based on equation Eq. (1) and Figure 5 following relationships can be found.

$$TPAeq = RD + \alpha$$
$$LPAeq = RD + (\alpha - 90°) \tag{2}$$

These relationships imply that a significant amount of material characterization can be performed on the skelp itself. Knowledge of the mechanical properties in the LPAeq and TPAeq directions will give an idea about anisotropic characteristics in the TPA and LPA directions (See Figure 6). However the pipe fabrication implies several steps of plastic deformation and heat treatment which can alter the final stress-strain behaviour. An in depth material characterization should therefore be performed on the pipe itself to ensure the representability of the actual material properties.
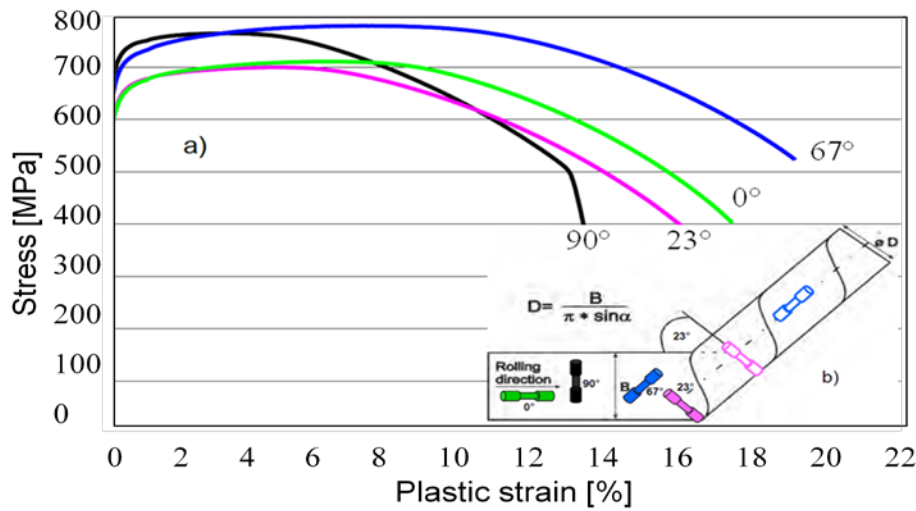

Figure 6: Stress-strain-curves of skelp samples (a) and their orientation to rolling direction (b) [32]

The forming process from the original coil to the pipe at the forming angle α leads to an increase of directional hardening and dislocation density in the hoop direction of the pipe. The hardening effect is dependent on the ratio of wall thickness to diameter of the pipe. The higher yield strength in the longitudinal

direction together with the additional stiffening effect of the spiral weld leads to a higher resistance to plastic deformation in longitudinal direction when compared to that in the hoop direction [32].

To maximize the representability, the whole production process should be taken into account. The first of three steps with major influences on the mechanical properties is the pipe forming from the coiled skelp. This step is followed by hydrotesting to ensure adequate strength and perform a leak detection. Finally the coating process imposes a thermal cycle on the pipe. Different trends are observed when comparing the strength properties of the skelp and pipe in hoop direction. To the authors' current knowledge these trends are influenced by test specimen geometry and preparation in which cold work hardening, heat treatment, residual stresses and the Bauschinger effect will be influential. Further research on the manufacturing process and its influences on mechanical properties is required.

For example, Collins et. al. found an increasing trend for yield strength in the hoop direction based on round bar specimens taken from several spiral pipes. During the forming of the pipe, the small amount of cold forming increases the average yield strength of the pipe with about 20 MPa. When the hydrotest is performed at a pressure theoretically resulting in a hoop stress equivalent to 100% SMYS, the average yield strength of the pipe was found to increase with about 20 to 40 MPa. The final thermal cycle introduces another increase of about 40 to 80 MPa [10, 25, 33]. Contrasting results were found by Thibaux et. al. [34] based on an industrial database containing test results based on flattened full-thickness specimens taken from spiral pipes with grades ranging from grade B to X80. Similar trends for flattened specimens were found by Collins et. al. [10, 25, 33].

For strain based design, the maximal strength is desired in the hoop direction (TPA) and the maximal ductility is desired in the longitudinal direction (LPA). These characteristics are inherently true for UOE-pipes, but not necessarily for spiral pipes where the forming angle and the directional anisotropy of the skelp are detrimental. This is represented in Table 1, which compares the yield and tensile strength properties in the longitudinal and transverse directions for UOE and spiral pipe.

Table 1: Comparison of yield and tensile strength properties between UOE and spiral pipe [10]

	Spiral pipe (Hydrotested)	UOE pipe (Expanded)
$\dfrac{YS\ in\ LPA}{YS\ in\ TPA}$	1.06	0.92
$\dfrac{UTS\ in\ LPA}{UTS\ in\ TPA}$	1.02	0.95

Bian et al. [10] found, based on six pipes, that both spiral and UOE pipes exhibited good work hardening. The hydrotesting process during spiral pipe manufacturing can be used to enhance the yield strength by cold work hardening in a similar manner to that of the expansion during the UOE-pipe forming. For a UOE pipe the yield and tensile strength are higher in the transverse than those in the longitudinal direction. For a spiral pipe, the transverse properties can be inferior to the longitudinal. Higher hoop strength is an advantage of UOE-pipes for achieving overmatch in the longitudinal strength properties of the girth welds.

3.2   Material characterization

For the determination of the mechanical strength properties, a number of tests should be considered. Yield and tensile strength have to be evaluated for the pipe base metal, the seam weld and its heat affected zone (HAZ). A further distinction should be made between the longitudinal direction (LPA) and the hoop direction (TPA).

Several test specimens can be used to determine the strength properties. At first, a round bar tensile specimen with a small diameter can be used to determine the stress-strain curve for specific areas. Another specimen type is a full thickness tensile strap. Here the stress-strain data will incorporate the whole thickness of the pipe wall. This specimen is easy to produce but requires flattening of the specimen when taken in the hoop direction, which induced a certain amount of cold work hardening and possible occurrence of the Bauschinger effect. A last tensile test procedure, the ring expansion test, uses a ring section of pipe of about 100 to 150 mm high. This ring is hydro-mechanically expanded to determine the stress-strain behaviour of the full thickness without the necessity of flattening the specimen.

To determine the yield and tensile strength in the longitudinal direction a full thickness strap specimen is commonly used because it is highly representative. The yield and tensile strength in the hoop direction on the other hand is accurately determined using the ring expansion tensile specimen. Since it requires a more complicated test rig (and driven by economical motivation) the round bar can be an alternative to measure the yield strength and the full thickness specimen to determine the tensile strength [25, 33, 35].

During design, the seam weld geometry and heat affected zone properties should be taken into account. Next to the geometry, the hardness and heat affected zone softening will be crucial for strain based design related projects [36]. The longitudinal properties of the seam weld can be characterized with a notched tensile specimen [37, 38].
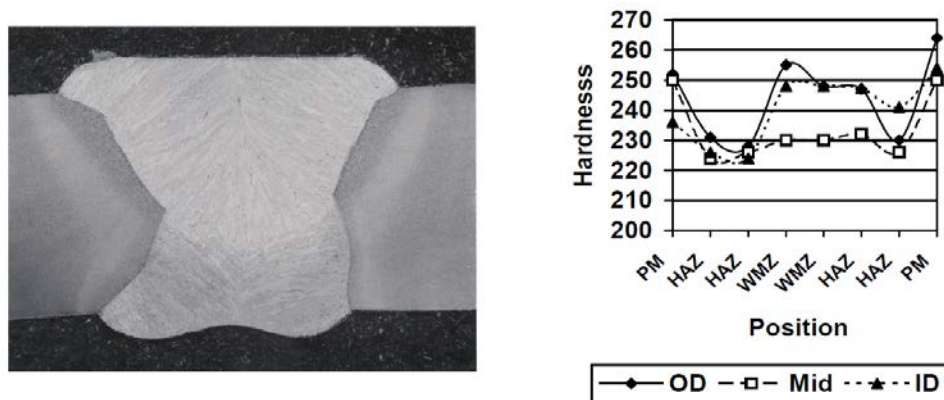

Figure 7: Cross section of a spiral weld and corresponding hardness profile [19]

In Figure 7 a typical hardness profile of an SAW spiral weld in a grade X80 pipeline steel is shown. At 1 mm from both the ID and OD surfaces, similar hardness values are achieved with the weld metal hardness closely matching that of the parent metal. At the heat affected zone up to approximately 10% of softening is observed. At mid-thickness, the hardness of the weld is reduced relative to the ID and OD regions. This effect is to be expected and likely to be caused by the additional heat input of the second weld pass.

Residual stresses are practically unavoidable when performing a weld. These residual stresses are caused by the local heat input during welding and its related local deformation. For a longitudinal seam weld (UOE pipe), these residual stresses will be symmetrical in the hoop direction. Since in a spiral welded pipe the seam is angled, a non-axisymmetrical residual stress distribution will occur. These residual stresses can be evaluated using a cut-ring test. The cut-ring test uses a pipe section of about 150 mm high and an axial cut is introduced in this section. Evaluation of the spring-back, spring-open or axial displacement will indicate the existence and location of residual tensile and/or compressive stresses [39].

4   CONCLUSIONS

When considering a spiral welded pipe in a strain based design context, specific attention should be given to the axial straining capacity of the pipe. This straining capacity is not only influenced by the anisotropy of the mechanical properties of the coiled skelp. Obviously the mechanical deformations and thermal treatments during the subsequent steps of the manufacturing process (forming, welding, hydrotesting and coating process) have to be considered. Further research is required to fully understand each individual influence and the effect of seam weld defects on local and global deformation capabilities.

5   REFERENCES

[1] "World energy outlook 2010," International Energy Agency 2010.
[2] Kan, W. C., Weir, M., Zhang, M. M., Lillig, D. B., Barbas, S. T., Macia, M. L., and Biery, N. E., "Strain-Based Design: Design Consideration Overview," Proceedings of Eighteenth International Offshore and Polar Engineering Conference.
[3] Denys, R., Andrews, B., Zarea, M., and Knauf, G., "EPRG Tier 2 guidelines for the assessment of defects in transmission pipeline girth welds," Proceedings of International Pipeline Conference, Calgary, Canada.
[4] Lillig, D. B., "The First (2007) ISOPE Strain-Based Design Symposium - A Review," Proceedings of the Eighteenth International Offshore and Polar Engineering Conference, 2008, Vancouver, BC, Canada.
[5] Mohr, W., 2003, "Strain-Based Design of Pipelines," {Minerals Management Project Number 434, (www.mms.gov/tarprojects/434.htm), October 2003}.
[6] Mohr, W., 2007, "Strain-Based Design: Strain Concentration at Girth Welds," {Minerals Management Project Number 47447 GTH}.

[7] Denys, R., Andrews, R. M., Zarea, M., and Knauf, G., "Update of the EPRG TIER 2 Guidelines on the Assessment of Defects in Transmission Pipeline Girth Welds," Proceedings of EPRG, 17th Joint Technical Meeting, Milan, Italy.

[8] "http://www.europipe.com."

[9] Rittmann, R., and Freier, K., "Niobium Containing Steels for Spiral and Electric Resistance Welded Line Pipe," (42630).

[10] Bian, Y., Pennington, C., Collins, L., and Mackenzie, R., "Evaluation of UOE ans Spiral-Welded Line Pipe for Strain Based Design," Proceedings of the 8th International Pipeline Conference, Calgery, Canada.

[11] Knoop, F. M., and Sommer, B., "Manufacturing and use of Spiral Welded Pipes for High Pressure Service: State-of-the-art," Proceedings of International Pipeline Conference, 2004, Calgary, Alberta, Canada.

[12] Peeck, A., 1985, "Cold Bending behaviour of large pipe of high strength," 3R international, 10, pp. 570 - 574.

[13] Zimmerman, T., Xie, J., Timms, C., and Asante, J., "Buckling Resistance of Large Diameter Spiral Welded Linepipe," Proceeding of International Pipeline Conference, 2004, Calgary, Alberta, Canada.

[14] Pumpyanski, D. A., Lobanova, T. P., Pyshmintsev, I. Y., Arabey, A. B., Stolyarov, V. I., Kharionovsky, V. V., and Struin, A. O., "Crack Propagation and Arrest in X70 1420x21,6mm Pipes for New Generation of Gas Transportation System,"Proceedings of 7th International Pipeline Conference, 2008, Calgary, Alberta, Canada.

[15] Wang, X., Barbas, S. T., Kibey, S., Gioielli, P., and Minnaar, K., "Validation of Strain Capacity Prediction Method - Comparison of Full-Scale Test Results to Predictions from Tearing Analysis Based on FEA," Proceedings of the 5th International Conference on Pipeline Technology, 2009, Ostend, Belgium.

[16] Knoop, F. M., Zimmermann, S., Flaxa, V., and Gross-Weege, J., "Mechanical Properties and Component behaviour of X80 Helical Seam Welded Large Diameter Pipes," Proceedings of the 8th International Pipeline Conference, 2008, Calgary, Alberta, Canada.

[17] "http://www.hydrocarbons-technology.com/."

[18] Yuqun, Y., Yixin, H., Yongkuan, Y., Daoyuan, W., Yonglong, W., and Stalheim, D. G., "The Development of X80 Steel Plate and Coil for the 2nd West-East Pipeline Project," Proceedings of 7th international Pipeline conference, 2008, Calgary, Alberta, Canada.

[19] Collins, L. E., Hamad, F., Kostic, M., and Lawrence, T., "Production of High Strength Line Pipe Steel by Steckel Mill Rolling and Spiral Pipe Forming."

[20] Hashemi, S. H., and Jalali, M. R., 2006, "Recent Developments in Manufacturing Processes of Ultra High-strength Gas Transportation Pipelines," 1st Iranian Pipe and Pipeline Conference, 2006(42630).

[21] Hashemi, S. H., and Jalali, M. R., "Evaluation of Fracture Initiation Energy in API-X65 Pipeline Steel," Proceedings of IPC 2008, 7th International Pipeline Conference.

[22] Hillenbrand, H.-G., Beirmann, K., Liessem, A., Heckmann, C. J., and Schwinn, V., "Development of High Strength Material and Pipe Production for Grade X120 Line Pipe," Proceedings of International Pipeline Conference, 2004, Calgary, Alberta, Canada.

[23] Akbarzadeh, A., 1997, "Effect of thermomechanical processing on microstructure, texture, and anisotropy in two Nb microalloyed steels," McGill University, Montreal, Canada, Department of Mining and Metallurgical Engineering.

[24] Hashemi, S. H., and Jalali, M. R., 2006, "Experimental Study of Charpy Impact Characteristics of High-Strength Spiral Welded Gas Pipeline," ASME Conference Proceedings, 2006(42630), pp. 57-63.

[25] Klein, R., Collins, L., Hamad, F., Chen, X., and Bai, D., "Determination of mechanical properties of high strength linepipe," Proceedings of 7th International Pipeline Conference, 2008, Calgary, Alberta, Canada.

[26] Hashemi, S. H., and Jalali, M. R., 2006, "Experimental Investigation of Directional Properties of Spiral Welded Gas Pipeline Steel," 1st Iranian Pipe and Pipeline Conference, 2006(42630).

[27] Sanchez Mourino, N., 2011, "Crystallographically Controlled Mechanical Anisotropy of Pipeline Steel," Ghent University, Belgium.

[28] Bae, J.-H., Choi, S.-H., Kim, K. S., and Kang, K. B., "Effect of Thermomechanical processing parameters upon texture development and anisotropy of mechanical properties of API-X80 line pipe steels for spiral welded pipes," Proceedings of International Pipeline Conference, 2004, Calgary, Alberta, Canada.

[29] "http://www.wk-industries.com."

[30] Knoop, F. M., and Flaxa, V., "Characterization of hot-rolled strips of up to 18.9 mm in thickness and their processing to helically welded large diameter pipes of grade X80," Proceedings of Pipeline Technology 2009, Ostende, Belgium.

[31] Bai, D., Collins, L. E., Hamad, F., Chen, X., Klein, R., and Zhou, J., "X100 (grade 690) Helical-Welded Linepipe," Proceedings of 7th International Pipeline Conference, 2008, Calgary, Alberta, Canada.

[32] Fonzo, A., Lucci, A., Ferino, J., Biagio, M. D., Spinelli, C. M., Flaxa, V., Zimmermann, S., Kalwa, C., and Knoop, F. M., "Full Scale Investigation on Strain Capacity of High Grade Large Diameter Pipes," 18th Joint Technical Meeting 16/19 May 2011, San Fransisco, CA.

[33] Chen, X., Collins, L. E., Hamad, F., and Bai, D., "The Evolution and Determination of Mechanical Properties during the Manufacturing Process of High Strength Spirally Welded Pipe," Proceedings of 6th International Pipeline Conference, 2006, Calgary, Canada.

[34] Thibaux, P., and Van Den Abeele, F., "Influence of forming operations on the yield stress measured on pipe," Proceedings of the 8th International Pipeline Conference, 2010, Calgary, Alberta, Canada.

[35] Collins, L. E., Bai, D., Hamad, F., and Chen, X., "High Strength Spiral Linepipe for Strain-Based Pipeline Designs," Proceedings of the Seventeenth International Offshore and Polar Engineering Conference, 2007, pp. 2969 - 2975.

[36] Mohr, W., "Strain-Based Design for Materials with HAZ Softening," Proceedings 6th International Pipeline Conference, 2006, Calgary, Alberta, Canada.

[37] Beddeleem, J., De Waele, W., Hertelé, S., Verstraete, M., and Van Minnebruggen, K., "Characterization of mechanical properties in weld metal using inverse modelling," Proceedings of Sustainable Construction And Design, 2012, Ghent, Belgium.

[38] Standards-Australia, 2002, "AS 2885-2 Pipelines - Gas and liquid petroleum," Welding.

[39] Weiwei, L., Chunyong, H., Qiurong, M., and Yaorong, F., "The Development of Large Diameter and Thickness X80 HSAW Linepipe," Proceedings of 7th International Pipeline Cenference, 2008, Calgary, Alberta, Canada.