STUDY OF SENT SPECIMENS WITH A TILTED NOTCH TO EVALUATE DUCTILE TEARING IN SPIRAL WELDED PIPELINE APPLICATIONS

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Abstract: There is an increasing interest for the use of spiral welded pipelines in strain based design applications. Environmentally imposed loads are able to plastically deform the pipelines, meaning that their structural response is of the utmost importance. However, since the influence of the spiral weld is not fully grasped, further investigation is necessary. The mechanical response of the pipeline is not only influenced by its material properties, but also by the angular position of the welds. Subsequently, the effect of mixed mode loading is a crucial aspect when assessing the helical welds. To evaluate the ductile tearing of the pipeline material, multiple single edge notched tensile (SENT) tests - each with a tilted notch of 25° with respect to the transverse direction - were executed. The extension of the crack is assessed by means of potential drop measurements and finite element simulations. Resistance curves were realized by combining the crack opening displacement with the associated crack extension. This is an ongoing investigation and in this paper a first set of five tests are evaluated.

Keywords: spiral welded pipelines; strain based design; voltage drop; abaqus; digital image correlation; SENT

1 INTRODUCTION

Due to a rising population growth, the demand for fossil fuels is ever increasing. Well-known oilfields become more and more depleted and new remote sources need to be explored. These sources are usually located in harsh environments which is troublesome for its extraction and transportation. Pipelines that transport these fossil fuels from the origin to the user encounter some challenging areas and climatological difficulties such as earthquakes, landslides or permafrost [1]. The environmentally inflicted loads can be alarming as there is a possibility that they impose longitudinal deformations of the pipeline which extend beyond the elastic range. Situations like these should be taken into account when designing pipelines and for this reason a strain based design approach is necessary because it limits the allowable strains rather than the allowable stresses which is the case in a stress based approach [2].

To evaluate the tearing resistance of pipelines, a Single Edge Notched Tension (SENT) specimen with the notch perpendicular to the loading direction is often used. However, these specimens might not be ideal for the characterization of the tearing resistance of spiral welded metal. In this paper a SENT specimen with the notch tilted with respect to the longitudinal direction of the specimen is proposed. Consequently, the notch experiences a mixed mode loading which results in an opening mode (mode I) and a shear mode (mode III) component. Because of this mixed mode behaviour, the Crack Opening Displacement (COD) consists of the vector sum of COD_I (crack opening because of mode I) and COD_{III}(crack opening because of mode III). These values can be obtained by means of the Digital Image Correlation (DIC) technique. Combined with the crack extension, which is evaluated by a combination of the Direct Current Potential Drop method (DCPD) and an electrical finite element model, tearing resistance curves can be constructed. This paper is part of an ongoing investigation and it focuses on the experimental evaluation of the tearing resistance of SENT specimens with a tilted notch.

2 MATERIALS AND TEST SPECIMEN GEOMETRY

The specimens evaluated in this paper are obtained from the non-welded base metal of a spiral welded pipe with a forming angle of 25°, an outer diameter of 1219 mm and a wall thickness of 23.7 mm. The material has a yield strength of 600 MPa, a tensile strength of 690 MPa and a uniform elongation of 6.1%. Five specimens with a notch tilt angle of 25°have been tested and all of the samples have a cross section of 20.0 mm by 20.0 mm (B = W) and a daylight grip length (H) equal to 10W [3]. The initial notch depth (a_0) is 5.0 mm which results in an a_0/W ratio of 0.25 (Fig.1).

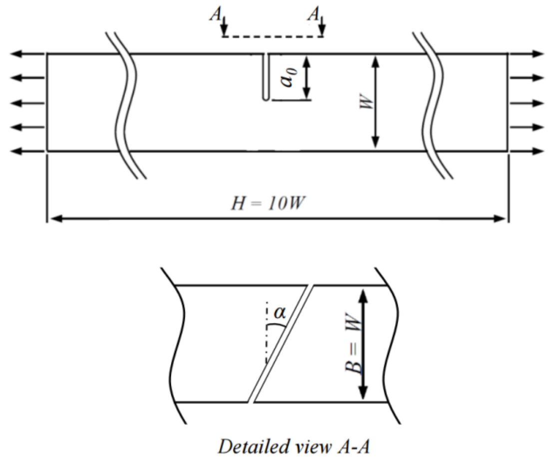


Figure 1 : Schematic representation of a SENT specimen with tilted notch.

The specimens are tested in a 1000 kN test rig in a displacement controlled mode. To achieve a satisfactory amount of ductile tearing, the specimens are loaded beyond their maximum in the load-displacement curve (Fig.2). The test procedure used for this paper is adopted from the Ph.D. dissertation of Matthias Verstraete [3-5].

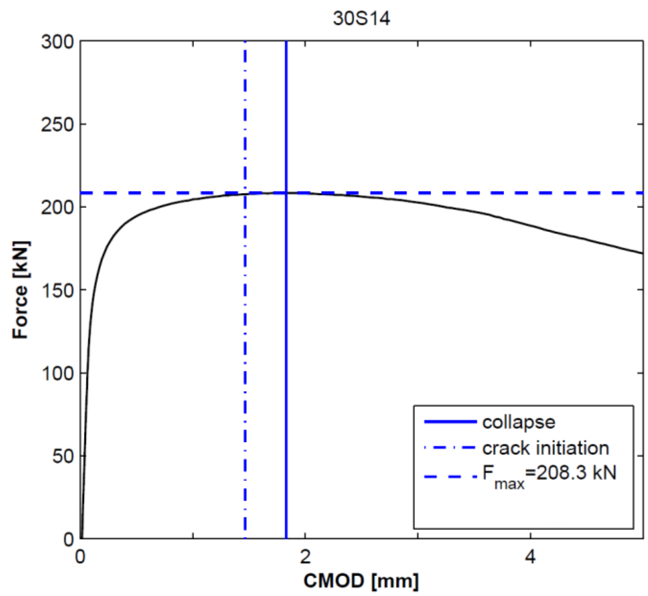


Figure 2 : Force-CMOD curve (α=25°, a_0/W = 0.25).

3 INSTRUMENTATION

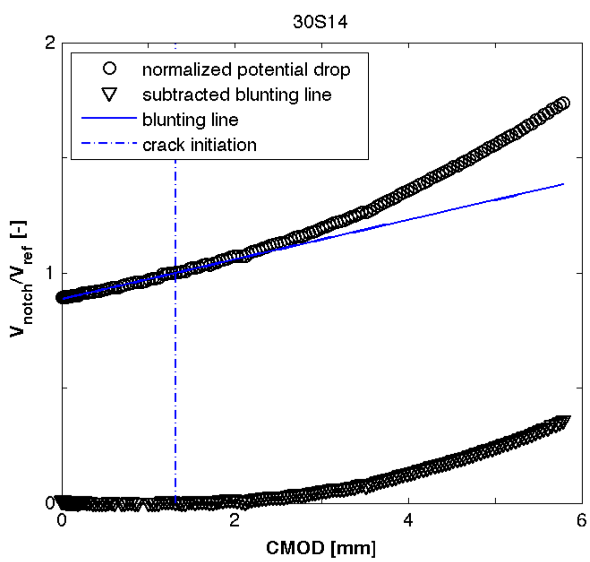
3.1.1 DIC

As the notch is tilted with respect to the longitudinal direction, a non-negligible mode III component will occur. As a consequence the evaluation of COD and CMOD cannot be performed by the traditional double clip gauge method because it cannot simultaneously measure the mode I and mode III opening of the notch. During the execution of the tests, Digital Image Correlation is used as an excellent alternative. Digital Image Correlation (DIC) is an optical technique based on a three-dimensional correlation of digital images taken from two different camera intervals. By processing images of the specimen in deformed and undeformed conditions, the deformation field at the specimen's surface can be determined [6].

3.1.2 Potential drop technique

The direct current potential drop method (DCPD) is based on the electrical conductivity of a metal and can be used to determine the stable crack growth in a specimen. While executing the tensile test, a constant current is sent through the entire specimen. Four probes that are located at a distance of 2.0 mm from the edges and 2.0 mm from the notch are used, measure an increase in voltage. As the tensile stress increases, the crack tip deformation starts with a blunting phase. This phase can be associated with a linear increase of the measured voltage which is caused by a change in the electrical resistance of the specimen due to plastic deformation. Once crack initiation starts, the measured voltage values will increase more than linear because the section of the specimen at the crack decreases [7].

For SENT specimens with a perpendicular notch, the stable crack growth can be obtained from the measured potential drop signals by means of an analytical formula postulated by Johnson [8]. However, this formula does not apply to specimens with a tilted notch. Here, the potential drop across the crack as a function of the crack size is modelled by means of an electrical finite element simulation developed in commercial software Abaqus. The simulation gives the voltage drop across the crack for different discrete crack sizes. Via this manner the crack size can be related to the accompanying voltage.



. **Figure 3: Dimensionless potential drop –CMOD diagram (α=25°, a_0/W = 0.25).**

Figure 3 shows the progression of the potential drop (normalized to the reference voltage) during testing of a SENT specimen with notch angle of 25° and initial relative crack depth $a_0/W = 0.25$. As all five tests have the same notch angle and initial notch depth, their results are similar. Therefore only one specimen will be discussed in detail. The finite element simulation does not cover the blunting of the material when imposed to an external load. As a result, the potential drop data cannot be directly associated with the data obtained from the simulations. To overcome this deficit, a blunting line (Fig. 3) is estimated as the tangent to the linear part of the voltage values up to the crack initiation. The values of the normalized potential drop are subtracted by the linear blunting line and then associated with the FEA to achieve the crack extension Δa_{PD} values. The crack extension caused by the blunting of the material (Δa_b) is evaluated by means of the initiation value of COD_I, as only mode I is expected to have an influence on the crack tip blunting.[8] Finally, the total crack extension can be evaluated as the sum of the crack extension extracted from the potential drop technique and the crack extension caused by the blunting of the notch. These relations are summarised in Eq. (1) and can be seen in figure 4.

$$\Delta a_b = \begin{cases} COD_I/2 & COD \leq COD_{init}/2 \\ COD_{I,\,init}/2 & COD > COD_{init}/2 \end{cases}$$
$$\Delta a_{tot,\,PD} = \Delta a_b + \Delta a_{PD} \qquad (1)$$

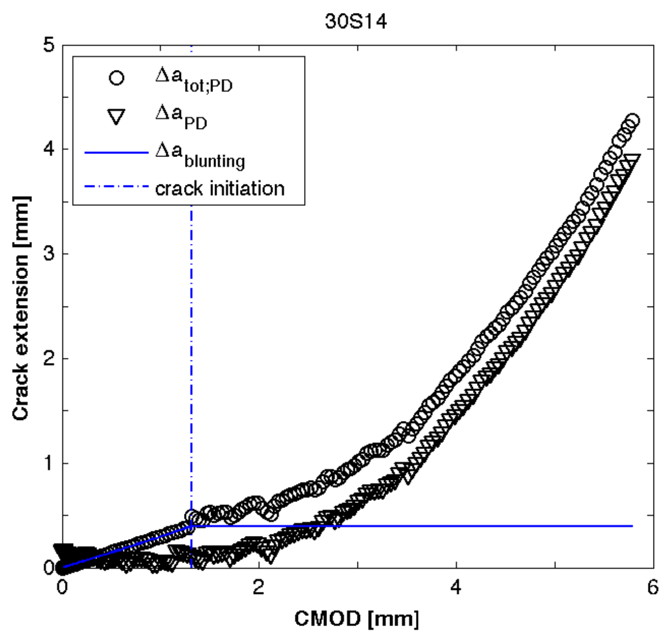


Figure 4: Crack extension –CMOD diagram (α=25°, a_0/W = 0.25)

4 TEST RESULTS

To achieve a fracture resistance curve, the fracture toughness parameter should be plotted against the crack extension. The data from the Digital Image Correlation provide the crack opening displacement in mode I and mode III as well as the total crack opening displacement (Eq. 2).

$$COD = \sqrt{COD_I{}^2 + COD_{III}{}^2} \qquad (2)$$

The Potential Drop method provides an evaluation of the crack extension. Combining these results gives the resistance curve illustrated in figure 5. It should be noted that COD_I and COD_{III} are very similar. Based on previous research [9], this result was expected and it is displayed more clearly in figure 6 which shows that the level of mode mixity (COD_{III}/COD_I) at a notch angle of 25° is practically constant and equal to one. Thus the mode I contribution to the crack opening is almost equal to the mode III contribution.

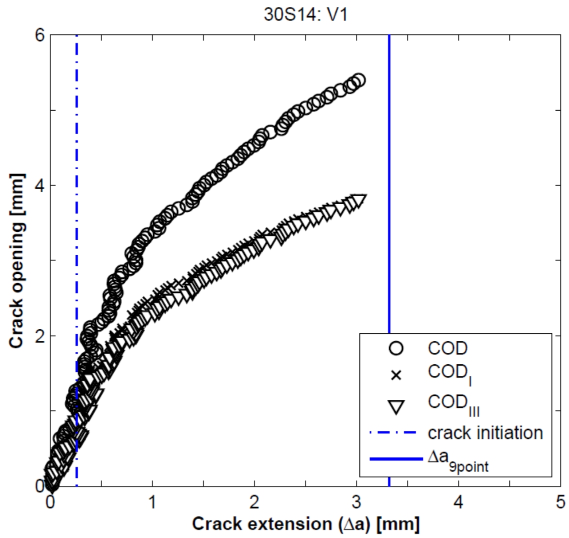


Figure 5: Fracture resistance curve for specimen 30S14 (total and separate for mode I and III) with an angle of α= 25°

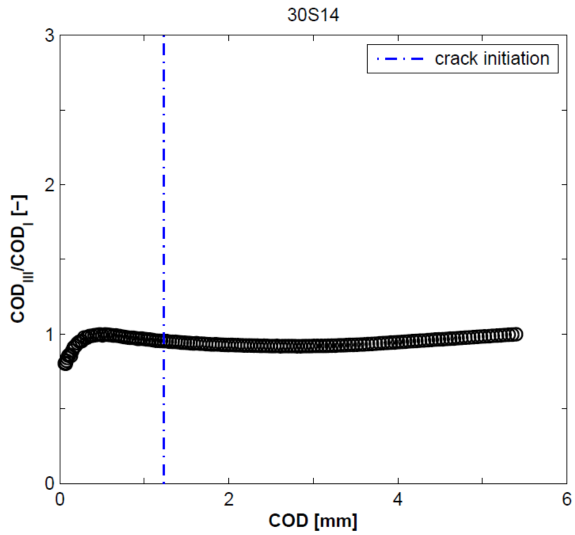


Figure 6: Level of mode mixity observed while loading of the specimen.

After the tests are executed, the final crack extension is be evaluated by means of the nine point average method [10]. Firstly, the specimen is heat tinted at 200°C for 3 hours. Afterwards it is cooled in liquid nitrogen and broken up in a brittle manner by means of a three-point bending apparatus. When a picture is taken from the fractured surface (Fig. 7), the ductile tear can be measured at nine equally divided positions.

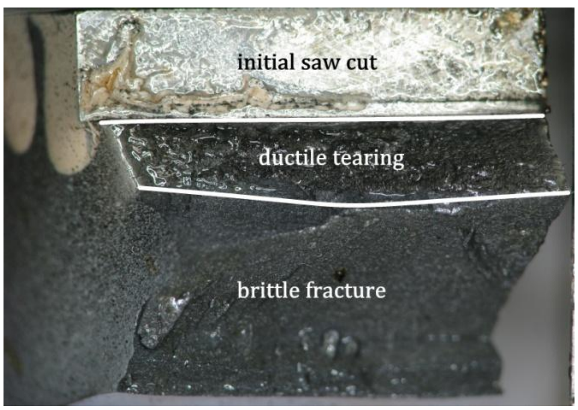


Figure 7: Fracture surface after heat tinting and brittle fracture (α=25°, a_0/W = 0.25).

According to the ASTM E-1820, the ductile tearing lengths at positions one and nine should be measured at a distance of 0.05W from the width of the specimen (Fig. 8).

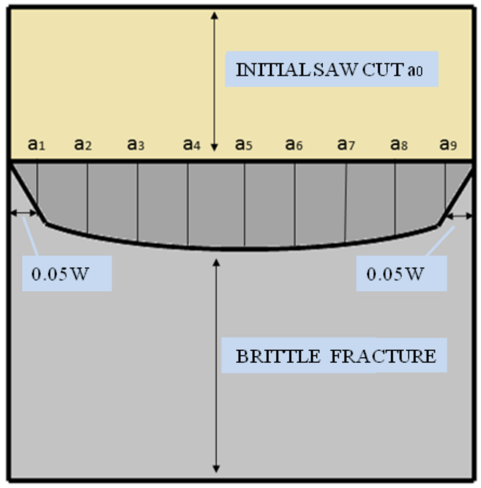


Figure 8 : schematic representation of the implementation of the nine point average method

The depth of the ductile tears near the edges of the specimen are averaged and added with the remaining seven tear depths as can be seen in Eq. (3).

$$\Delta a_{9point} = \frac{1}{8}\left[\frac{a_1 + a_9}{2} + \sum_{i=2}^{8} a_i\right] \quad (3)$$

The so determined crack extension has been added to figure 5. Note that the total crack extension measured with the potential drop technique is very close to the value measured according to the nine points average method. This observation gives confidence in the developed DCPD methodology.

5 CONCLUSIONS

When assessing spiral welded pipelines, a strain based design approach should be implemented. To evaluate the effect of mixed mode load conditions (I and III) on the tearing resistance at flaws in spiral welds, SENT specimens with slanted notches can be used to obtain crack growth resistance curves. Both the COD and the CMOD can be calculated with the use of DIC, while the crack growth can be assessed through the potential drop method. This paper shows that COD_{III} is approximately equal to COD_I for SENT specimens with a notch tilt angle of 25°. The final crack extension values determined using the DCPD methodology are in close correspondence to the actual final crack extension values. Also, the results obtained from the five tested SENT specimens showed a low amount of variation which indicates the stability of the used test procedure.

6 NOMENCLATURE

a_0	initial notch depth	[mm]
B	width of specimen	[mm]
CMOD	crack mouth opening displacement	[mm]
COD	crack opening displacement	[mm]
COD_I	crack opening displacement for mode I	[mm]
COD_{III}	crack opening displacement for mode III	[mm]

H	daylight grip length	[mm]
W	height of specimen	[mm]
α	notch tilt angle	[°]
Δa	ductile crack extension	[mm]
Δa_{9point}	ductile crack extension measured by nine point average method	[mm]
Δa_b	ductile crack extension by blunting	[mm]
Δa_{PD}	ductile crack extension estimated with PD	[mm]
$\Delta a_{tot,PD}$	ductile crack extension + blunting estimated with PD	[mm]
DIC	digital image correlation	
SENT	single edge notched tension	
DCPD	direct current potential drop	
FEA	finite element analysis	

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Lillig D. B., "The First Isope Strain-Based Design Symposium - A Review," Proc 18th International offshore and Polar Engineering Conference, ISOPE, Vancouver, Canada

[2] K. Van Minnebruggen , W. De Waele , R. Denys and P. Thibaux, "Strain based design considerations for spiral welded pipelines", Ghent University, OCAS N.V., Belgium

[3] M. Verstraete, "Experimental-numerical evaluation of ductile tearing resistance and tensile strain capacity of biaxially loaded pipelines", Ph.D thesis, Ghent University,2013.

[4] S. Hertelé, M. Verstraete, K. Van Minnebruggen, R. Denys and W. De Waele, "UGent guidelines for SENT testing" Proc 6th International Pipeline Technology Conference, Ostend, Belgium

[5] M. Verstraete, R. Denys, K. Van Minnebruggen, S. Hertelé, and W. De Waele, “Determination of CTOD resistance curves in side-grooved Single-Edge Notched Tensile specimens using full filed deformation measurements”, Engineering fracture mechanics.

[6] S. Hertelé, M. Verstraete, K. Van Minnebruggen, R. Denys and W. De Waele, "Applications of digital image correlation in girth weld testing" Proc 6th International Pipeline Technology Conference, Ostend, Belgium

[7] M. Verstraete, K. Van Minnebruggen, S. Hertelé, R. Denys and W. De Waele, "Determination of tearing resistance in SENT and CWP specimens using direct current potential drop measurements" Proc 6th International Pipeline Technology Conference, Ostend, Belgium

[8] Johnson, H. H., 1965, “Calibrating the Electric Potential Method for Studying Slow Crack Growth”,Materials Research and Standards, pp. 442

[9] K. Van Minnebruggen, M. Verstraete,, R. Denys, P. Thibaux, W. De Waele, “Determination of CTOD resistance curves in SENT specimens with a tilted notch” , Proceedings of the 10th International Pipeline Conference, 2014, Calgary,Canada

[10] American Society of Testing and Materials, 2011, E 1820 -Standard Test Method for Measurement of Fracture Toughness.