EVALUATION AND INSTRUMENTATION OF THE DROP WEIGHT TEAR TEST

Servaas Vervaet[1], Wim De Waele[2]

[1] Ghent University, Belgium
[2] Ghent University, Laboratory Soete, Belgium

Abstract

With the use of high strength and high toughness steels in the pipeline industry it has become necessary to better understand the factors which influence the reliability and integrity of oil and natural gas pipelines. The Drop-Weight Tear Test (DWTT) is a common test method to determine the fracture appearance and fracture ductility of steel. Its fundamental purpose is to determine the appearance of propagating fractures in steels over the temperature range where the fracture mode changes from brittle to ductile. But there are still many subjects of discussion concerning which results must be obtained, in which manner they should be obtained and how they should be interpreted. Is it still possible to deduce a shear appearance from samples which have such an abnormal fracture that they used to be discarded as invalid ? Could results from the DWTT be correlated with the Crack Tip Opening Angle (CTOA), which is particularly important for finite element modelling ? What to think about methods such as the two specimen CTOA and the simplified single specimen method ? How severe is the effect of tunnelling in contemporary linepipe steels and how can this be dealt with ? Many questions still remain and many aspects are still vague despite the correlating ecological, economical and safety issues. Therefore, there is a major necessity for further investigations.

Keywords: DWTT; Abnormal Fracture Appearance; CTOA

1 INTRODUCTION

A high degree of integrity and reliability of pipelines is needed for several reasons. First of all to guarantee a constant supply of oil and natural gas which have become indispensable in our society. Secondly because it is difficult to locate a defect in a huge network of pipelines which or often remote and/or buried. Third aspect is the high repair cost, certainly in case of cracks which can propagate through several segments. Finally one should also take the safety of persons and the ecological aspects in consideration. Although integrity and reliability might not seem to be a high demand for a few kilometres of pipes, one has to keep in mind that this becomes much more difficult to achieve when we are talking about hundreds or thousands of kilometres. The following examples illustrate these rather vague terms with concrete numbers. The U.S. operates almost 4 million kilometres of natural gas and hazardous liquid pipelines. Between 1989 and 1998, 2241 pipeline incidents occurred, resulting in 226 deaths, 1030 injuries, $ 700 million in property damage and release of 1,5 million barrels of crude oil and gasoline [1]. Although much knowledge and experience has been gathered, further investigations are still required. This not only to better understand and control the same processes of the last decades, but also because of the higher demands on the working conditions and the new materials used.

Nowadays, linepipe steels with high strength and excellent low-temperature toughness are needed to transport oil or natural gas produced in extremely cold regions such as Alaska and Siberia. Steels with higher strength and toughness are needed because one tends to increase the thickness and diameter of pipelines in order to raise their transportation efficiency over long distances.

2 BATTELLE DROP WEIGHT TEAR TEST

To evaluate the fracture properties of linepipe steels, various laboratory testing methods which try to closely correspond with full-scale fracture behaviour have been developed. Previously, in low toughness steels, the resistance to ductile fracture propagation generally showed a linear relation with the (upper shelf) absorption energy measured from Charpy impact test. However, in high toughness steels with high absorption energy, this correlation is less obvious. Consequently this test is replaced by the (Battelle) Drop Weight Tear Test or (B)DWTT (Figure 1). Large scale experiments (West Jefferson or WJ tests) revealed that a correlation exists between percentage shear area and transition temperature of DWTT specimen and the full-scale pipe, see Figure 2 [2].

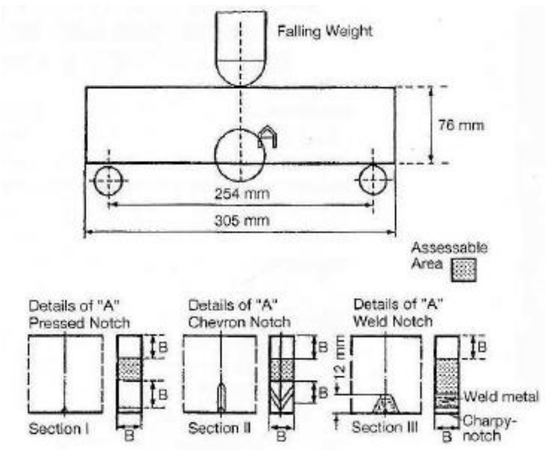

Figure 1: Schematic representation of BDWTT set-up [2].

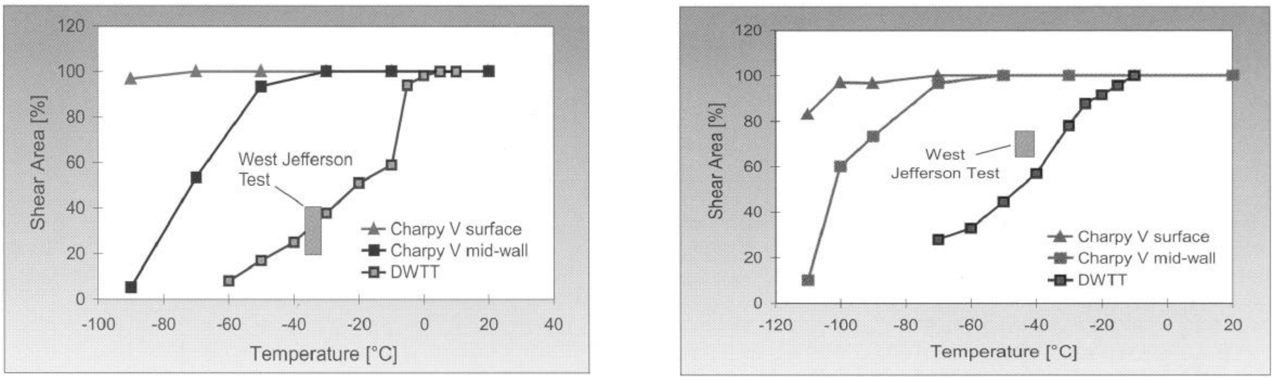

Figure 2: Comparison of transition temperature obtained by Charpy impact test, BDWT test and West Jefferson test [2].

The broken sample from the DWTT is inspected to determine the percentage of the area that failed by shear fracture, called the shear appearance. When this value is 85% or more (Battelle criterion) the steel is supposed to have sufficient toughness and will not exhibit brittle fracture behaviour in full-scale conditions. The temperature at which this threshold is reached is called the shear appearance transition temperature and is assumed to have a very good match with the Fracture Propagating Transition Temperature (FPTT) of an actual pipeline.

Other characteristics of the DWTT, such as the load-displacement diagram of Figure 3, are often measured and might give a clearer result, but its usefulness should be further investigated. Another trend in the modelling of stable crack growth is the use of CTOA. This is a measurement which can be used in many different tests, but is rather difficult to obtain in a DWTT because of the high speed. As a result various theories have been developed to correlate CTOA with other characteristics obtained in the DWTT.

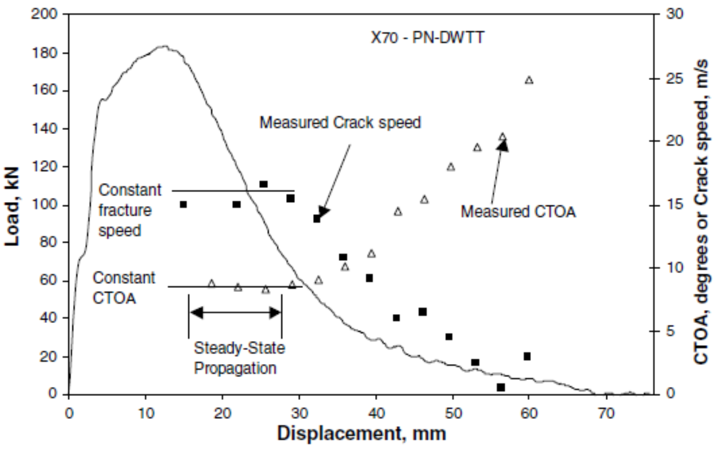

Figure 3: Experimental CTOA and load versus displacement for
a DWTT specimen from an X70 linepipe steel [3].

3 ABNORMAL FRACTURE APPEARANCE

In practice, one has to determine and quantify which part of the DWTT specimen has been broken by shear and which by cleavage fracture. The distinction between shear and cleavage fracture becomes more difficult and subjective with the use of high strength and high toughness steels because of their abnormal fracture appearance. In such case some samples should be discarded. According to the most widely used standard, namely the API 5L3 [4], a sample that does not exhibit cleavage fracture at the notch tip is invalid. This is questionable, as it becomes almost inevitable with the use of the high strength steels [5,6]. Furthermore, most types of abnormal fracture appearance are not mentioned in the standard. The figure below shows three different types of abnormal fracture appearance which have each their own intrinsic causes. By gaining knowledge of these causes, we can better judge the results and/or reduce their occurrence.

Figure 4. Three types of abnormal fracture appearance in DWTT specimens [6].

In the first type, the so-called “inverse fracture” appears. A cleavage fracture mode occurs in the hammer impacted zone of the fracture surface where the width of fracture surface increases abruptly. This fracture originates from the enhanced transverse compressive strain which is produced by the coupled effect of hammer compression, bending of the specimen and the frictional force of the test machine supports, at the hammer impact region. Rolling supports of the test machine could reduce the frictional force and the transverse compressive strain of specimens during fracture, and so reduce or prevent this type of abnormal fracture appearance. [6]

In the second type of abnormal fracture appearance, a large cleavage fracture zone extends from the centre to the end of the fracture surface. The residual thickness around this zone is clearly larger than the original thickness of the specimen. Along with this compression, the toughness of the material has degraded. This abnormal fracture appearance problem can be partially solved by using an alternative notch type instead of the conventional pressed notch. Examples are a static pre-crack, a fatigue pre-crack, an electron-beam weld, and the most frequently used chevron notch [5,6]. Thanks to the sharp notch that gives a higher constraint, a reduction of the fracture initiation energy is obtained. This also means a reduction of the maximum load during fracture and the region influenced by the hammer impact. However this chevron notch has a few disadvantages. There is for instance a larger variation in the test results, which depends on the variation of the machined notches. The chevron notch has a more complicated shape than the pressed notch and requires a higher level of precision. The higher cost of machining is also a disadvantage for its use in quality control of products. Consequently, the API 5L3 standard recommends the pressed notch for lower toughness linepipe steels and the chevron notch for high toughness linepipe steels [4]. This recommendation is rather vague despite of a non negligible influence of this choice on the shear appearance.

The third type of abnormal fracture appearance is characterized by a large region of cleavage fracture which is restricted to the centre of the fracture surface. Here the residual thickness of the cleavage fracture zone is smaller than the original thickness of the specimen at the fracture surface. The cause of this type of fracture is the change of stress state and dynamic effect during crack propagation, and is impossible to prevent by modifying the notch shape and/or the test method. This fracture type corresponds to the intrinsic fracture behaviour of materials and it is therefore not justified to regard these specimens as invalid [6]. But this specific zone of cleavage fracture may, according to several authors, not be included in the shear area percentage rating [5,6].

Contrary to the third type, the first and second type show a local increase in thickness and compression deformation. This does not correspond to the fracture of an actual bursting pipeline where there is a decrease of the pipe wall thickness as a result of the three-dimensional crack tip stresses. Therefore the second type of abnormal fracture appearance cannot be evaluated. In the first type however, the cleavage region is small and lies often out of the region of evaluation so that these samples can be treated as valid [5,6].

4 CRACK TIP OPENING ANGLE (CTOA)

4.1 General

The breakdown in the usefulness of Charpy upper shelf energy as a predictor of fracture toughness has led investigators, since the 1980s, to look towards more theoretical approaches based on fracture mechanics variables such as crack-tip stress or strain, crack tip opening displacement (CTOD), crack tip opening angle (CTOA, see Figure 5), crack tip energy release rate. Several important research institutes have concluded that the most appropriate variable for modelling stable crack growth is the CTOA measured at a specified distance from a crack tip [7].

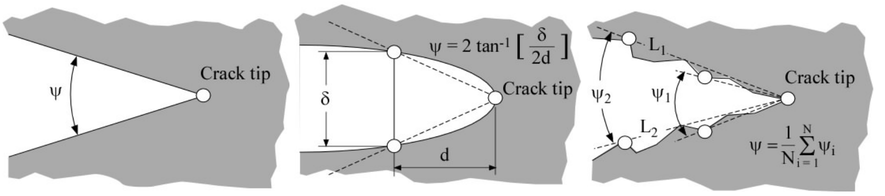

Figure 5. Different techniques to measure the CTOA.

The use of elastic-plastic finite element analyses to simulate fracture of laboratory specimens and structural components using the CTOA criterion has expanded rapidly. The possibility to model in 3D was an important step forward because it allowed to simulate a more appropriate state of stress at the crack tip whereas one had to assume plain-stress or plain-strain behaviour with 2D models [8]. Although the constant CTOA criterion has been successfully applied to numerous structural applications such as aircraft fuselages and pipelines [8], there are still many aspects which remain doubtful. For instance the clearly notable higher value of the CTOA at the beginning of the crack propagation is normally neglected. The variation of the CTOA value through the thickness of the specimen is only recently observed and needs to be further investigated along with the effect of crack tunnelling [9,10]. These effects are normally not considered in a simulation, but tend to become more important with the utilization of higher strength and toughness materials. Figure 6 shows an example of the tunnelling effect in an interrupted DWTT specimen [10].

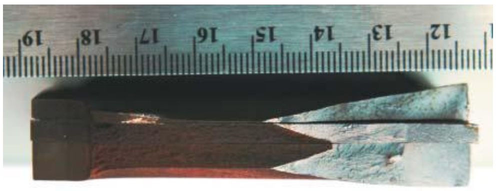

Figure 6. Tunnelling in an interrupted DWTT specimen [9].

4.2 Optical measurement

The fracture propagation in a DWTT specimen at normal speed takes only a few milliseconds so that the use of an expensive high-speed camera is necessary. During fracture it is (almost) impossible to measure the CTOA at the interior of the specimen. One possibility is to interrupt the test by stopping the falling mass using two rigid steel cylindrical blocks [11]. Another possibility is to execute the test quasi-statically, but this will influence the result [9,10]. Subsequently the specimen can be cut in two by electrical discharge machining [1] or one can use the specimen as a kind of mold to make a silicon negative of the crack after which it is possible to perform measurements [10].

Several methods exist for the actual measurement of the angle. The most commonly used are represented in Figure 5 and Figure 7. A first method uses data from the crack profile to fit lines from the crack tip to pairs of reference points back from the crack tip. Hereby the difficulty lies in the exact localisation of the crack tip. Another method uses points located near this tip instead of the crack tip itself and consider the increment. A third method, is to calculate the angle of two lines which are each fitted with several points. Besides these methods, one need also to decide at which distance one should measure behind the crack tip and if one uses points on the crack edge or further away from it. These choices have their influence on the mean value and the deviation of the CTOA [1,12].

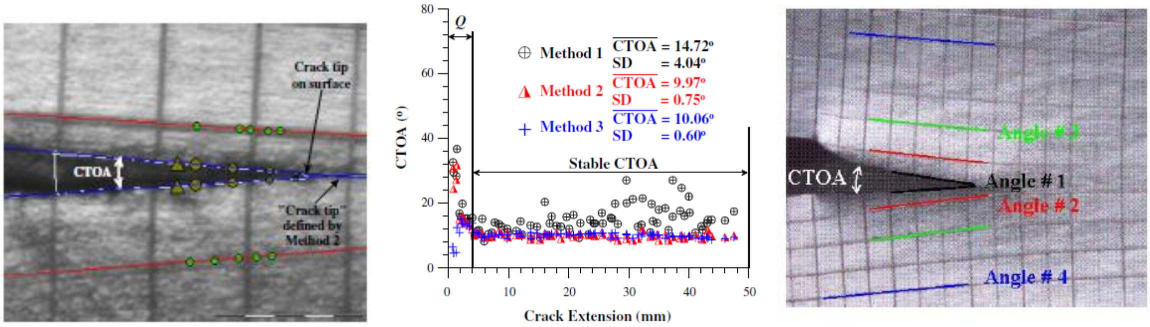

Figure 7. CTOA measurement methods [1,12]. (a) different methods to determine the angle, (b) measurements according to the different methods of a, (c) measurements further from the crack edge.

4.3 Indirect measurements

Several methods exist to circumvent the difficulties of a direct measurement. They all make use of the load-displacement diagram. Measurements therefore do not demand extra labour and test machines are often already installed with the right equipment.

One technique which worked quite well for lower toughness steels, is the two specimen DWTT. By using the absorbed energies from two specimens with different notch depths and subtracting one from another, one tried to eliminate the unwanted influence of the initiation energy. Results obtained for higher toughness steels were not satisfying [3].

Another method is to evaluate the propagation energy which is assumed to be absorbed after the peak load. A linear relationship between this propagation energy and sin(2*CTOA) is observed, but still needs more validation [7].

A more recent method called the simplified single specimen (S-SSM) method uses the slope of a logarithmic load displacement diagram measured in the steady-state region as most important parameter in their calculation. Figure 8 shows a few results of which the correlation of the S-SSM method with the mid-section CTOA looks promising [9].

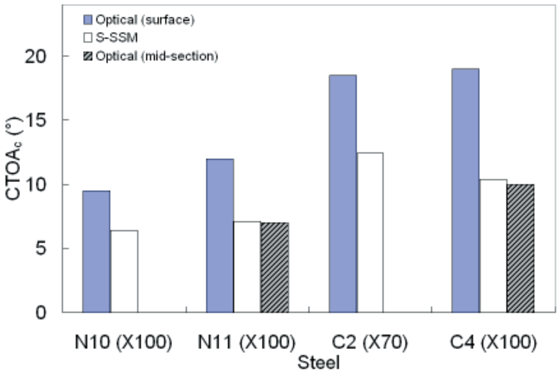

Figure 8. CTOA for quasi-static DWTT by different measurement methods [9].

5 CONCLUSIONS

Further investigations for an adequate DWTT method for the determination of the toughness of modern line-pipe steels are needed. With the utilization of increasingly higher strength and toughness materials has grown the difficulty to evaluate linepipe steels with the percentage shear appearance. This is a qualitative testing method which needs to be adapted and verified with full scale burst tests for new materials. But a successful correlation for one type of high toughness steel and its abnormal fracture appearances shall not be automatically useful for other steels. Performing these experiments for each new type of steel would be too expensive. That is why a shift to more fracture mechanics based testing methods, which would need less expensive verification, is probable. This could for example involve the use of the Crack Tip Opening Angle (CTOA). These measurements are well known in other laboratory tests such as the compact tension specimen, but are not often used in the DWTT. A direct optical measurement of the CTOA in a DWTT could bring more clarification as it combines both the frequently used experiments of the DWTT with the theory of CTOA. Some other already existing methods using the DWTT are also promising but need more tests to evaluate their usefulness and reliability.

6 REFERENCES

[1] National Institute of Standards and Technology, Pipeline Safety, http://www.nist.gov/mml/materials_reliability/upload/853_07_02b.pdf

[2] M. Erdelen-Peppler, R. Gehrmann, G. Junker, G. Knauf, A. Liessem, Significance of DWT testing for line pipe safety, Proceedings of the 11th Int. Conf. on Fracture, Turin (Italy), 2005, 6 pages.

[3] D.L Rudland, G.M Wilkowski, Z Feng, Y.-Y Wang, D Horsley, A Glover, Experimental investigation of CTOA in linepipe steels, Engineering Fracture Mechanics, Vol70, Issues 3-4, 2003, Pages 567-577.

[4] API R 5L3, Recommended practice for conducting drop-weight tear test on line pipe, API, 1996

[5] B. Hwang, S. Lee, Y.M. Kim, N.J. Kim, J.Y. Yoo, C.S. Woo, Analysis of abnormal fracture occurring during drop-weight tear test of high-toughness line-pipe steel, Materials Science and Engineering: A, Volume 368, Issues 1-2, 2004, Pages 18-27.

[6] Z. Yang, C.B. Kim, Y. Feng, C. Cho, Abnormal fracture appearance in drop-weight tear test specimens of pipeline steel, Materials Science and Engineering: A, Volumes 483-484, 2008, Pages 239-241.

[7] N. Osbrone, Instrumented Drop Weight Tear Test, Imatek, 2008

[8] J.C Newman Jr., M.A James, U Zerbst, A review of the CTOA/CTOD fracture criterion, Engineering Fracture Mechanics, Volume 70, Issues 3-4, 2003, Pages 371-385.

[9] S. Xu, W.R. Tyson, R. Eagleson, C.N. McCowan, E.S. Drexler, J.D. McColskey, Ph.p. Darcis, Measurement of CTOA of pipe steels using MDCB and DWTT specimens. In : Proceeding of the 8th International Pipeline Conference, Calgary, Canada, 2010

[10] E. Marotta, M. Minotti, P. Salvini, Effect of fracture tunneling in DWT Tests, Engineering Fracture Mechanics, 2011,

[11] S. Xu, R. Eagleson, W.R. Tyson, and D.-Y. Park, Crack tunneling and crack tip opening angle in drop-weight tear test specimens, Int J Fract 2011; DOI 10.1007/s10704-011-9635-5

[12] Ph.P. Darcis, C.N. McCowan, H. Windhoff, J.D. McColskey, T.A. Siewert, Crack tip opening angle optical measurement methods in five pipeline steels, Engineering Fracture Mechanics, Volume 75, Issue 8, 2008, Pages 2453-2468.