УДК 669.018.298.3

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INVESTIGATIONS ON THE APPLICABILITY OF CRACK ARREST PREDICTIONS FOR HIGH STRENGTH LINEPIPE AT LOW TEMPERATURES

Abstract

Fracture propagation in gas transmission pipelines is a major concern for the operation of high pressure lines. Therefore, the resistance against propagating fractures is one of the main requirements for these pipes. To date, ductile fracture resistance is commonly measured with Charpy impact tests and the most widely applied concept to predict pipe behaviour is the Battelle Two Curve (BTC) method which was developed in the 1980's on basis of the material available at that time. Limitations of this methodology have been shown in the last decade, especially on grades exceeding X80, for which it was not possible to yield reliable predictions. Recent full scale tests on X80 for arctic conditions underlined this once again.

Alternative testing methods as well as refined concepts to predict structural behaviour have been investigated by researchers around the world. Nevertheless, there is no clear indication as to which modification of either testing methods or concepts may solve the problem. Within this paper, a review of the state of the art is given and the most promising alternatives are highlighted. Based on this, a thorough assessment of the results of a fracture propagation test on grade X80 is conducted. Calculations with BTC for the test set-up with air pressurisation at a temperature of –10 °C lead to a Charpy impact requirement below 250 J. The test itself revealed that pipes with CVN energy above 300 J could not arrest the propagating fracture. On the other hand, the energy measured in BDWT tests showed a better correlation to the arrest properties of the pipes. Different specimen preparation methods in terms of notch insertion were compared to identify the most suitably set-up to correlate with full scale test results.

Introduction

Fracture propagation in gas transmission pipelines is a major concern for the operators of high pressure gas pipelines. The phenomenon of a propagating fracture is marked by a complex interaction between the pipe and the escaping gas. Moreover, it is an extremely fast process.

Ductile fracture resistance is commonly measured with Charpy impact tests. The impact energy measured is transferred to the pipe fracture resistance by semi-empirical correlations. Originally, these formulae were calibrated on lower strength lower toughness steels with impact energies below 100 J where laboratory test results were correlated to the results of full scale fracture propagation tests.

The most commonly used model is the Battelle Two Curve (BTC) model proposed by Eiber, Bubenik and Maxey [1] that is considered to yield reliable predictions when applied to material with properties close to those used for the calibration of the model. The approach deals with gas decompression and crack propagation resistance as uncoupled processes that are both dependant on the fracture propagation velocity.

At the time of the calibration of the BTC model, and with the material properties that were basis for this calibration, the prediction worked well. As development proceeded and both strength and toughness increased, pipes with toughness above the calculated arrest toughness did not actually arrest the propagating fracture. Test results of pipes of grade X80 and above are depicted in Figure 1. If the model worked for these grades, the 1:1 line should separate arrest (solid symbols) and propagation (open symbols). It is clearly evident that this is not the case. Therefore, correction factors have been proposed to overcome these limits for grade X 80.

In contrast, a valid solution could not be verified for grade X100. The solution seemed to be given applying a correction factor of 1,7. Then, a test series conducted within an EC- funded project lead to propagation in pipes with Charpy-V energy far in excess of this level [2].

Recent full scale fracture tests on X80 for arctic conditions have once again shown the limitations of the methodology when applied outside the verified boundary conditions even though the correction factor for X80 had been applied [3]. The authors observed a reduced deformation in terms of wall thinning adjacent to the crack path in combination with separations on the fracture surface in those pipes that did not successfully arrest the crack.

Several potential factors causing the non-arrestabiliy of high strength pipes have been identified and discussed without having found a final explanation, let alone solution, to date:

- Reduced deformability/ductility (high Y/T ratio, little strain hardening);

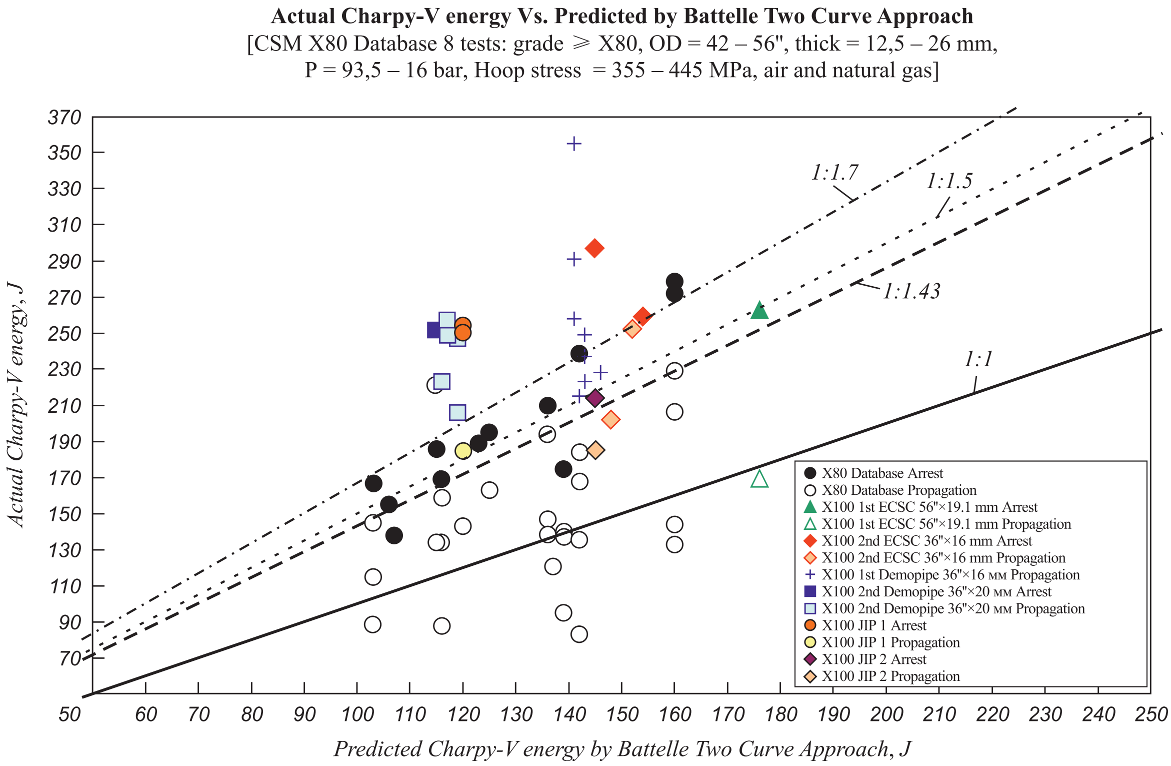

Figure 1. Actual versus predicted Charpy-V energy by BTC model for high grade steel (after Demofonti et al., [2])

- Shift of proportion of crack initiation and crack propagation towards relatively higher initiation;
- Issue of significance of separations and other formations on the fracture surfaces of both laboratory and full scale test specimens;
- Problems with meaningful laboratory specimens; limitations of Charpy impact test for high strength high toughness steel (specimens commonly do not break when impact energies exceed around 200 – 250 J; Charpy impact test does not discriminate between initiation and propagation energy).

To overcome this situation, considerable amount of research was directed towards alternative test methods to measure the resistance against a propagating fracture in a laboratory scale and refining existing methods.

Alternative testing methods

Instrumented BDWT test

As an alternative to insert Charpy-V energy in the BTC model, the model was calibrated against DWTT energy. Instrumented DWT tests have the advantage of a longer ligament, the full wall thickness and discrimination between initiation and propagation energy. A certain drawback is given by uncertainty of measurement that is to some extent governed by different testing and evaluating methods that are used for this non-standardised test in different laboratories.

The first attempts were made by substituting Charpy-V energy by total DWTT energy. With high grade high toughness steels, the problem of decreasing percentages of propagation energy in relation to total energy was not resolved. Therefore different attempts were made experimentally to deplete the initiation energy. Back-slotted [4], pre-cracked [5] and brittle notch specimens [6] were thoroughly investigated. A real break-through was not achieved, although certain improvements were visible. Authors of [7] stated that using DWTT energy there was no need for correction as the grade increased. Other investigations showed a good description of full scale fracture resistance by DWTT propagation energy [8]. On the other hand, it has been demonstrated that the DWTT energy can give a good indication of fracture resistance but the differences between the energy in arrest and propagation condition in very 2 high strength steel can be that minimal that they may be within the scatter band of production test results [2].

CTOA

CTOA as a parameter to describe the resistance against a propagating fracture has been discussed since the ‘80s [9]. First applications have been made in the aerospace industry on aluminium sheets. Here, it has been observed that the CTOA at initiation is usually high but after a very short length of crack extension remains stable at a lower level (Figure 2, [10]).

Unfortunately, the CTOA depends on the ligament length. An increasing ligament leads to a decreasing CTOA. Effectively, this means that a transferability criterion has to

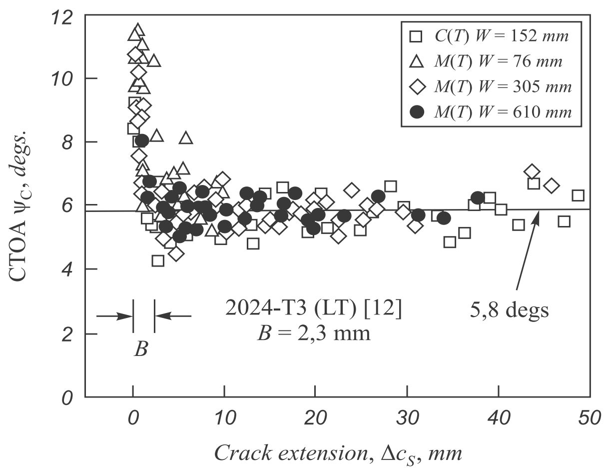

Figure 2. CTOA measurements in aluminium sheet specimens (after Newman et al. [5])

be found to relate the value measured on laboratory specimens to a propagating ductile fracture in a pipe.

Experimentally, different techniques have been investigated to measure the CTOA of a pipe section.

The **Two Specimen CTOA** method proposed by Demofonti et al. [11] is based on testing two sets of DWTT specimens having different ligament lengths. The difference in consumed energy of the two specimens is assumed to be the propagation energy of a crack of the length equal to the difference between the two ligament lengths. The critical CTOA is calculated utilising the total energy measured in the test. The procedure has been successfully applied to lower strength low toughness pipes [12] but has some limitations in high strength high toughness steels (Charpy energy > 200 J). It has been modified trying to eliminate the increasing portion of initiation energy by testing pre-cracked, back-slotted and Chevron notched specimens (e.g. [13]). Some success has been demonstrated with these modifications in high strength steels [14]. However recent work has sown that a large uncertainty remains depending on the applied parameters in the calculation of CTOA (in the example between 3,1° and 11,6°) [15].

The **Single Specimen** method uses results of SEB tests to determine the CTOA [16]. As for the Two Specimen method, uncertainties in calculation result from the use of different factors for rotation of plastic hinge, geometric constant and dynamic flow stress. To overcome certain problems, the **Simplified Single Specimen** method was developed that does not require the use of the dynamic flow stress, that cannot be directly determined, instead it is an estimated value [17].

Alternatives to testing DWTT specimens have been investigated e.g. modified double cantilever beam specimens that were proposed by several authors [18, 19]. The specimen design has some advantages as having a long ligament and not requiring flattening whereas the test set-up is sophisticated in comparison to the DWTT set-up. The deformation at the crack tip is measured with digital and video cameras that need to have a high resolution. Prior to testing, the specimen has to be pre-cracked. The authors of [19] state that they found a large variation in measured CTOA values due to irregular crack edges and difficult crack tip identification. They conclude that more research work is necessary to apply this method to improve the results.

The methods for single specimen CTOA estimation need a sensitive instrumentation and detailed analysis to derive the CTOA value, thus difficulties are to be expected when conducting these tests as production tests. Furthermore, the comparison between laboratory and full scale tests indicate larger deviations in high strength steel. Effectively, this means that exactly the problem of high strength steels is not better solved with this approach [20]. In the end, empirical correlations may still be needed to apply this approach.

Instrumented Charpy impact test

Leis [21] demonstrated an improvement of the prediction of the BTC model for modern high strength steels using the results of Charpy impact tests with a correction factor (Figure 3). To derive this correction factor, results of instrumented impact tests to distinguish between initiation and propagation energy were investigated.

Refinement of methods

The greatest effort was made to refine the BTC model that deals with fracture resistance and driving force as uncoupled processes and yields reliable predictions for low grade steels. Most authors worked with correction factors to calibrate the model against the deviating predictions.

CSM adaptation of BTC model (BTC-CSM)

CSM proposed a correction factor of 1,7 for pipes of grade X100 [22]. The factor is purely empirical comparing

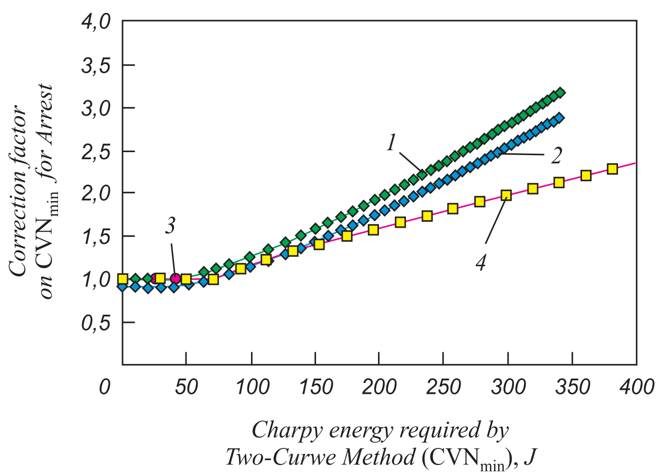

Figure 3. Different correction factors developed on the Charpy energy for ductile fracture arrest with the TCM:
1 – Wilkovski 1977 equation for X70 and lower-grade steels;
2 – Wilkovski equations with staticstical correction from full-scale tests for X70 and lower-grade steels;
3 – Feamehough 1977 data; *4* – Leis 2000 equation

predicted CVN arrest toughness to actual arrest toughness observed in a number of full scale tests. At the time being, the factor seemed suitable whereas later it turned out that even this high correction factor lead to non-conservative arrest predictions.

Leis adaptation of BTC model (BTC-LEIS)

By separating the contribution of initiation and propagation energy of Charpy impact tests, Leis [23] derived a formula to calculate the required Charpy-V energy for steels with more than 100 J impact energy that is given by:

$$CVN_{BTC-LEIS} = CVN_{BTC} + 0,002CVN_{BTC}^{2,04} - 21,18, \quad (1)$$

the effect of the equation is to increase the required toughness as the values calculated with the original BTC model increase. The author reported improvements in prediction in comparison to the original model.

Wilkowski adaptation of BTC model (BTC-WILK)

Based on instrumented DWT and Charpy-V tests, Wilkowski [24] reported a formula similar to Leis in that the originally calculated BTC arrest energy is corrected if the energy is above a certain level.

$$BTC_{WILK} = 0,056\left(0,1018CVN_{BTC} + 10,29\right)^{2,597} - 16,8. \quad (2)$$

The correlating results of instrumented, modified DWT that minimise the initiation energy and Charpy-V impact tests, the contribution of the both energy terms in the impact tests was estimated.

High strength linepipe (HLP) committee model

The high strength linepipe (HLP) committee in Japan [25] developed a simulation model that is a dynamic variant of the BTC method that is able to calculate the length of the propagating fracture. The method is reported to give good predictions up to grade X80. An additional feature of this method is the substitution of Charpy-V energy by pre-cracked DWTT energy. A revaluation of fracture propagation test results of high strength steels (mostly X100 and above) showed some improvement in predictions, particularly in terms of fracture speed (Figure 4). On the other hand, the arrest energy was not predicted correctly, as was the case with the original BTC model.

Sumitomo model

Based on the investigation of uncertainties of key variables which influence the predictions of the HLP model, new equations for the crack velocity curve were developed [26]. With this adjustment further improvement of the prediction of crack velocity was achieved. After revaluation of results of X100 tests, a number of by then not correctly predicted propagation results became explainable.

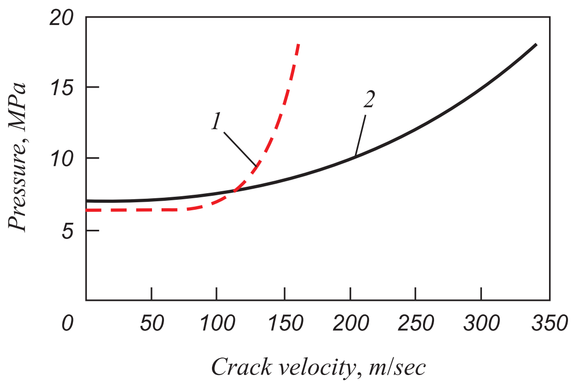

Figure 4. Comparison of crack velocity curves predicted by Battelle and HLP equation (after Makino et al. [25]). Preducted crack velocity for the 2nd ECSC Test's initiation pipe. Experimentally measured maximum crack velocity is abt. 310 m/sec:
1 – Battelle (Eq. 1): *2* – HLP (Eq. 5)

The authors concluded that intrinsic crack arrest could be achievable in X100 after having found explanations for unexpected propagation with their model.

Further thoughts

Leis posed the question whether toughness in traditional terms is the correct parameter to discriminate between pipes that have the capability to arrest and pipes that haven't [27]. Instead, by analogy to fracture initiation, it can be assumed that beyond a certain toughness level the failure becomes flow-stress controlled. If this were the case, fracture would be a propagating tensile instability rather than a running fracture. In consequence, totally different test methods might be required to describe the properties. It will be interesting to see in the future if research can confirm these ideas.

Experimental activities

Further in-house investigations were conducted on the pipe material similar to that utilised for the full scale fracture propagation tests reported in reference [3]. Different types of material in terms of susceptibility to formation of separations were investi-gated; they are consecutively numbered as 1, 2 and 3.

As instrumented BDWT tests may provide a viable alternative to Charpy impact tests while having some specific problems concerning the interpretation of the energy term, intensive investigations have been undertaken to give a better understanding of the test. For this purpose, the instrumented test rig was equipped with a laser system to measure the position of the hammer continuously throughout test and a high speed video system monitor the crack and specimen deflection.

In order to optimise crack initiation, the specimens were notched with pressed and Chevron as well as pre-cracked notches. Temperature transition curves were recorded with BDWT as well as Charpy impact tests.

Initially, both Charpy and BDWT tests were conducted and assessed in the "traditional" method. In addition to this, lateral expansion and separation index were determined for each specimen.

Charpy impact tests were conducted according to ASTM (Figure 5, *bottom*) and ISO (Figure 5, *top*) using an impact tester with 600 J energy. The closed symbols represent unbroken specimens while the open symbols represent broken specimens. The first, and most obvious, observation is that most specimens remained unbroken down to temperatures of –80 °C. Even at energy levels of 150 J (see Figure 5, *top*, *triangles*) it was not possible to separate the specimens of at least one material. On the other hand, in ASTM tests, there are two broken specimens marked with arrows in Figure 5, *top*, that did break and, while doing so, showed distinctively lower energy values than the unbroken specimens tested at the same temperature. The difference of the energy values recorded testing the non-broken specimens and the broken specimens reaches a factor of up to 1.7. This observation does not hold true for material high, in which the majority of specimens broke in ASTM testing and where the difference between the energy values of broken and unbroken specimens is not as expressed as described before. As a general rule, and as was expected ASTM tests yielded higher energy values in the upper shelf region. Looking at the diagrams, one can receive the impression of looking at transition regions of tested material in the temperature range shown. In reality, down to temperatures of –60 °C, the either did either not break at all or showed 100 % shear area. The first evidence of brittle fracture was visible at –80 °C for all materials in ISO tests and at –80 °C in ASTM tests of material high and –100 °C in the other materials with the exception of 2 outliers at –80 °C.

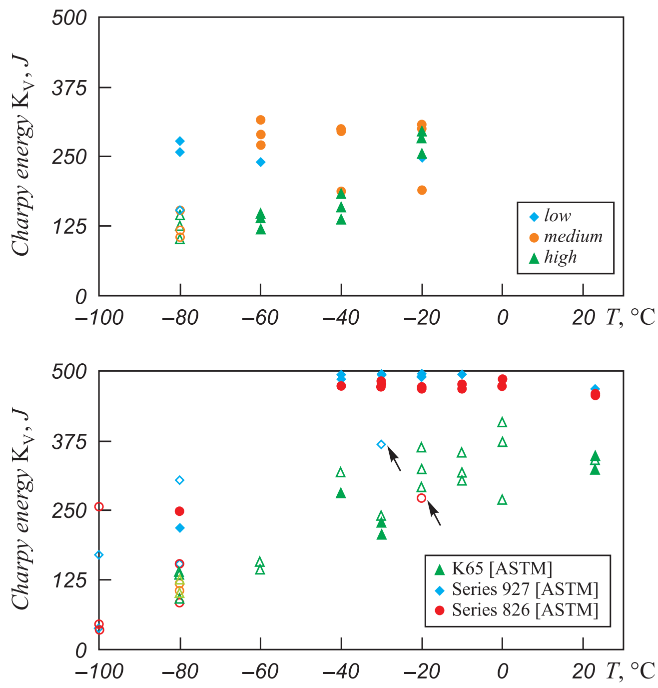

Figure 5. Results of Charpy impact tests

The evaluation of lateral expansion and separation index was not possible for most of the specimen. Nevertheless, by inspecting the fracture surfaces, separations were evident to a varying degree in most specimens.

Standard BDWT tests with pressed notch specimens were conducted and the fracture surfaces evaluated according to API5L (Figure 6). As expected in comparison to Charpy impact test, as an effect of the larger specimen size of BDWT resulting in a higher constraint, the transition curve is somewhat shifted to higher temperatures. The differences between the three materials is less expressed than in the Charpy impact tests, although both medium and high separation material show slightly lower shear areas at the same temperature. The low separation material could fulfil typical requirements down to –40° C whereas the other materials would qualify only above –10 °C. Concerning the energy consumed in the course of the test, no significant difference was observable between the materials. The values ranged within a scatter band without showing any relevant trends. The three notch preparation methods, namely pressed, Chevron and pre-cracked, were expected to influence the crack initiation. Pressed notch is the commonly used standard notch that is inserted by pressing a relatively blunt notcher into the specimen. This procedure results in plastification just ahead of the notch that can produce a higher resistance against crack initiation especially in high strength steels. To account for this, it is allowed to use Chevron notches to ease crack initiation. To enhance this effect, but used only for research purpose and not foreseen in codes and standards, a fatigue pre-crack can be inserted in the BDWTT specimen. If care is taken not to plastify the material ahead of the crack tip, this procedure will produce an infinitely sharp notch resulting in a minimum resistance against crack initiation. In theory, the crack propagation phase in terms of both fracture surface and consumed energy should not be influenced noticeably by the type of notch. If this assumption is true, the initiation energy as well as the total energy could decrease in specimens containing Chevron and fatigue notches whereas propagation energy should remain constant.

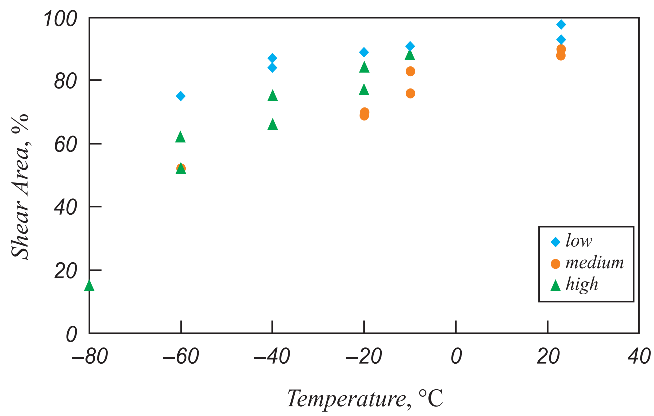

Figure 6. Results of pressed notch BDWT tests

By means of example, test results of low separation material are shown above (Figure 7). In contrast to theory, the Chevron notch yields the lowest energy in both initiation and propagation phase. While this effect is more pronounced in the initiation phase, it seems from these tests that the propagation phase is influenced by the notch type, too. On the other hand, with the exception of the medium material, the fracture surface is not influenced by the notch type at all.

Concerning possible correlations between separations and energy consumed or deformability of the specimens, no clear tendency was observed. Separations occurred in the upper region of the transition regime when shear areas were above 75%. The materials expected to show medium and high separation indices did exhibit distinctive separations on the fracture surface whereas the other material was almost free of separations. Whereas the actual separation index of the high and medium material was relatively similar within a common scatter band, the appearance of the surfaces did differ to some extent. The separation in the high material had a somewhat sharper angle to the outer surface. Despite the described differences, there seemed no clear correlation neither lateral expansion, that remained totally untouched by the formation of separations and was influenced only by the shear areas, nor the consumed energy itself.

In order to facilitate a deeper understanding of the evolution of a crack in the BDWT test, further equipment was installed on the drop weight tower. A laser system was used to measure the position of the hammer at any time during

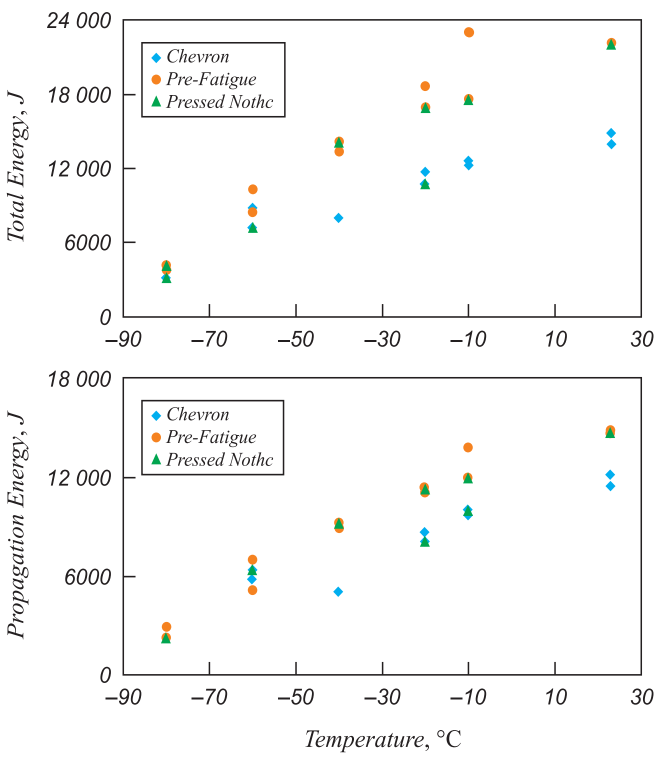

Figure 7. Comparison of BDWT tests of pressed, Chevron and fatigue notched

the test. This is important information as the velocity of the hammer is needed to calculate the consumed energy. Commonly, and without measuring the actual speed, this is achieved by recording a force versus time graph and calculating with the following equation:

$$\Delta E_0 = E_a\left(1-\frac{E_a}{4E_0}\right)=\bar{v}\int_0^{\tau}P(t)\,dt, \qquad (3)$$

where the velocity is approximated by:

$$\bar{v}=\frac{1}{2}\left(v_0+v_f\right)=v_0\left(1-\frac{E_a}{4E_0}\right). \qquad (4)$$

The energy values calculated with equation (1) and the actual velocity deviate by less than 1%. As this was validated in a number of tests, the approximated equation was used for the calculations thereafter.

Normally, without deeper knowledge of the exact point of fracture initiation, the pragmatic approach is to suppose that the crack initiates at the point of maximum force and the specimen is broken when the signal equals zero. The area prior to maximum represents the initiation energy, the other the propagation energy. When correlating the propagation energy to the shear area on the fracture surface, a large scatter is often found. A potential force for this scatter is the discrepancy between the portion of the fracture surface considered for the evaluation of shear area and the portion of the force versus time graph that does not coincide as described above. It may be expected to minimise the scatter by calculating the propagation energy belonging to that portion of the specimen on which the fracture surface is actually evaluated. The video images can be of help by identifying the start and stop time in the graph.

Figure 8 shows a force versus time graph and the corresponding frames recorded by the video system at the equivalent time. The images show clearly that a single stable crack develops later than the curve reaches its maximum. The first signs of crack initiation appear in the region marked in orange on the plot. The corresponding image is shown on the left. The image on the right shows the first signs of a stable crack developing and corresponds to the beginning of the linear portion of the graph. Another important finding is related to the end of the linear part of the graph: as can be seen in the digital images, the specimen is by far not broken at that time. As a matter of fact, approximately one third of the specimen width remains untouched at that time. On the other hand, the specimen deflects strongly from that point onwards. This leads to an undefined stress-state in which the supports, the friction and hammer have a strong influence on the consumed energy as opposed to the crack being the only energy consumer. Therefore, this portion of the force versus time graph should not be considered when calculating the propagation energy.

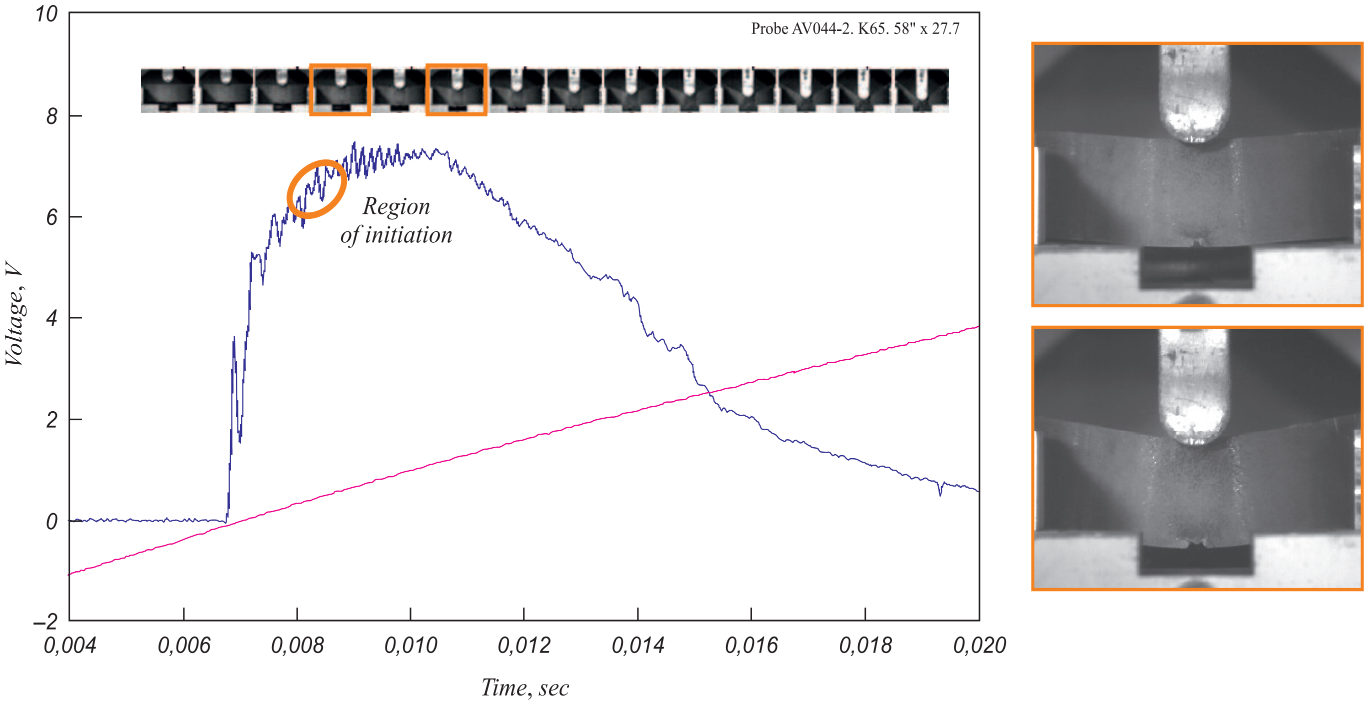

Figure 8. Pressure versus time graph and synchronised images of the crack developing in the specimen

The force versus time graphs of the three tested materials were reassessed according to the method described above. As could be expected, lower propagation energies were calculated now. On the other hand, the specific energy was found to be both higher and lower than the specific energy calculated by the "traditional" method, depending on the curve of each BDWT test. The test series completed to date do not allow for a statistical firm conclusion on the scatter, for the time being. It will be interesting to study this point in future work. Figure 9 shows the calculated energy as a function of the shear area. In this graph, it seems as if the energy in the high separation specimens marks the lower bound compared to the other materials.

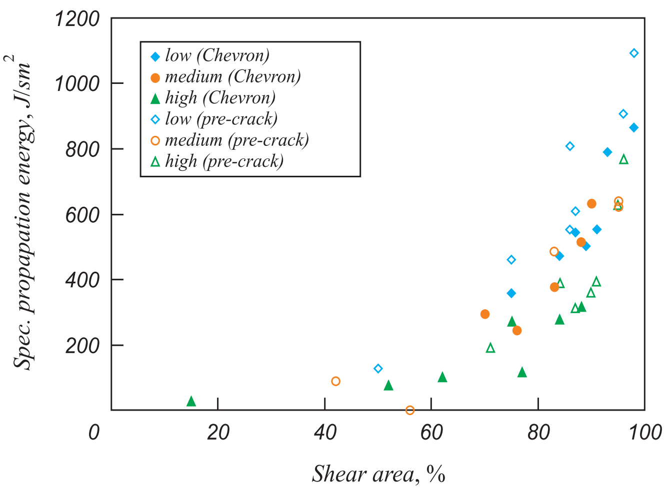

Figure 9. Propagation energy calculated from steady-state portion within BDWT test

Correlation to full scale test result

As mentioned above, the material investigated within this paper was tested within full scale fracture propagation tests. The pipes were of grade K65 with an outer diameter of 56″ and a wall thickness of 27,7 mm. The test section was pressured with air at 150 bar and the test was conducted at –10 °C.

On basis of the BTC method, an arrest toughness of around 150 J was calculated. Knowing that the original BTC model underestimates the required arrest toughness, a correction factor of 1,43 should be applied, thus leading to a required toughness of around 200 J. As can be seen in Figure 10, with the exception of one pipe, each pipe involved

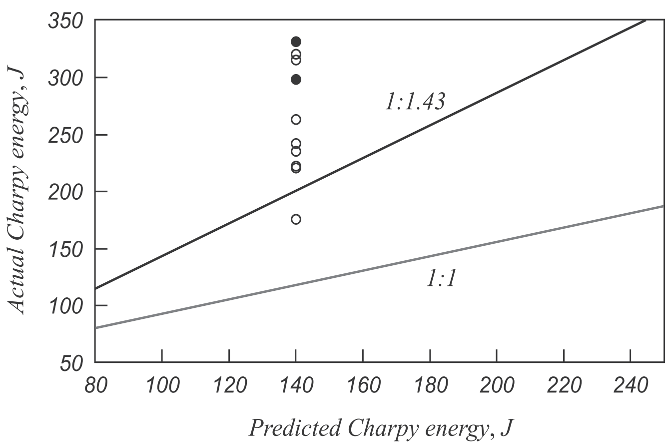

Figure 10. Actual Charpy energy vs. energy predicted by BTC method: ○ – propagation; ● – arrest

in the test should have arrested the propagating fracture. In reality, most pipes were propagation pipes, except for two arrest pipes. These had Charpy-V impact energies of more than 300 J. On the other hand, two propagation pipes had impact energies of 310 J.

This result shows that an unambiguous prediction is not possible on basis of BTC, even applying the recommended correction factor. Clearly, due to the relatively high pressure, the required Charpy-V energy is very high (compared to the original levels of below 100 J) and the question concerning the significance and applicability of such high impact energy must be posed.

On the other hand, the total DWTT energies seem to allow discrimination between arrest and propagation pipes (Figure 11). Interestingly, these seven pipes lie within a very close scatter band concerning the Charpy-V impact energies whereas the DWTT energies do vary around 50 %. The test result implies that pipes with specific total energy of around 800 J/cm^2 cannot arrest the propagating fracture whereas pipes with DWTT energy of more than 1000 J/cm^2 can arrest the fracture in the above test conditions. Obviously, this is a purely empirical observation valid solely for the underlying test conditions. Nevertheless, it gives an indication that DWTT results are better suited to describe fracture resistance of high strength steels.

Summary and conclusions

Moving outside the database of full scale fracture propagation tests against which the empirical or semi-empirical models were calibrated increases the probability of receiving non-conservative predictions. It was recognised that this is the case especially for high strength (grade X80 and above) steels.

Intensive investigations have been conducted to understand the background and overcome the problem. Within this scope, other test methodologies were subject of investigation and existing models were refined. To date, these efforts did not produce new solutions that solve the problem.

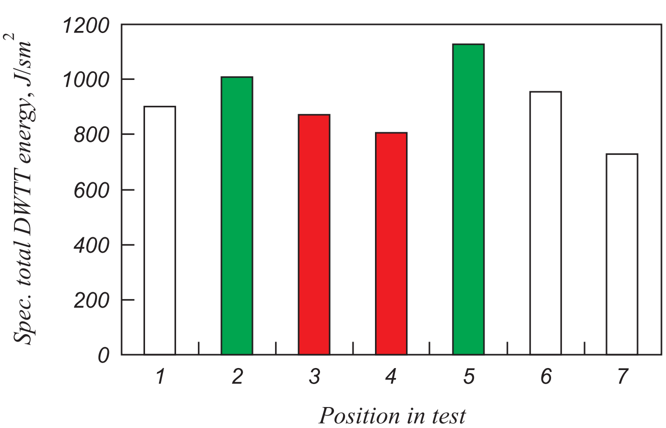

Figure 11. Specific DWTT total energy of pipes tested in a fracture propagation test:
□ – not involved; ■ – propagation; ■ – arrest

A promising alternative candidate to the Charpy-V impact test to determine the material resistance against propagating ductile fracture seems to be the DWT test that combines some advantages of the impact energy (e.g. suitability for production testing) with properties that can help to overcome the limits of the impact test (ligament size, full wall thickness and discrimination between initiation and propagation energy). Material of grade K65 tested in full scale fracture propagation tests was investigated in this context. Publications concerning these tests implied that an interrelation between the formation of separations and non-arrestability of pipes had been found. Therefore, lab tests conducted within this presenting work were aimed at identifying possible evidence for reduced toughness or deformability of material showing separations. The findings may be summarised as follows:

- A noticeable trend towards specimen not breaking in Charpy tests was found. The difference in consumed energy between broken and unbroken specimens was expressed at higher temperatures whereas moving towards lower temperatures, the values converged;
- Moving towards low temperatures in Charpy impact tests reduced the energy consumed while not breaking specimens down to –80 °C;
- ASTM tests yielded even higher impact energies of almost 500 J. It is highly questionable if these high numbers have any significance at all;
- BDWT energy discriminated better between arrest and non arrest pipes;
- Chevron and fatigue notch specimens could not decrease crack initiation resistance, on basis of this test series no benefit of these more labour- and cost intensive notch preparation methods was identified;
- There was no clear correlation between fracture surface in terms of separations in lab tests and the arrestability of pipes in full scale tests. In particular, the consumed energy in BDWT and the lateral expansion scattered at comparable separation indices;
- The steady-state portion of the force versus time graph should be taken when calculating the propagation energy. To come to comparable results, it is either necessary to monitor this condition exactly or a common procedure should be developed to ensure comparable evaluation independent of the operator of the tests.

On basis of these findings, the question of suitability of Charpy impact tests to predict fracture arrest in high strength material is underlined strongly once again. Further work will be dedicated towards BDWT tests as a promising alternative is seen there. The drawback for the time being lies in the fact that instrumented tests are currently not standardised and the optimum evaluation of propagation energy requires either further instrumentation or a fixed procedure. The latter can be difficult in some cases of doubt where a steady-state portion cannot be easily identified on the graph itself. In addition to testing, a strong emphasis will also be laid on FE modelling that can be of valuable assistance in understanding the tests. First results will be published shortly [28]. Additionally, the dynamic crack resistance will be evaluated by means of BDWT tests and deflection measurement. This is expected to provide further information that will help to reliably predict crack arrest in high strength in future.

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Received November 10, 2011.