DEEP FRACTURE PROFILE EFFECT ON DWT TEST FOR PIPELINE CHARACTERIZATION

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Abstract

The paper focuses on the fracture of a SENB specimen in a Drop Weight Tear Test. Deep fracture profile occurring during stable propagation is investigated. Typically in the models that correlate the instrumented test results to CTOA values, the position of the fracture development is assumed straight, i.e. independent to specimen thickness. With this assumption in mind, the residual ligament computation is apparently easy. On the contrary, a remarkable fracture tunneling is present: it looks like different pipeline materials present a different attitude to crack tunneling. In order to know the real shape of the fracture, silicone casts of DWT fractured specimens were made when stable propagation is achieved. The casts are analyzed through tomographical approach. Through the image processing of DWT tests, it is possible to automatically compute the angle of opening at the superficial crack tip during propagation as well as the overall kinematics during loading. The attention is finally centered on two different steels used in inshore gas piping, X60 and X100, detailing the comparison on the effective stress field acting nearby the crack tip and the energy really involved for the fracture propagation. The loads are applied making use of inclined constraints that allows to change the stress field ahead the crack tip, during the tests. As illustrated within the paper, the highest slopes allow to realize a persistent state of stress ahead the crack tip. This diffusive state of stress has an influence on X100 fracture behavior much more evident than that observed on X60.

1. Introduction

Gas Pipelines are generally manufactured by using low-alloy steels. However, the mechanical characteristics of pipelines have been increased significantly with time. Pipeline diameters and gas operating pressure have both increased with the aim to improve the overall load capacity of gas lines [1]. New generations of pipelines came one after the other, so that hoop stress operating limits could reach up to almost 900 MPa [2]. In the typical used measuring scale of strength, the evolution began from the X52 API up to the actual X100 or X120.
Ductile fracture resistance of pipelines is a very important issue to ensure that any possible catastrophic event might be limited to a restricted area. To check fracture resistance, a considerable number of full-scale burst tests have been performed all over the world [3]. All test results concern the capability of a pipeline to arrest the running of a longitudinal crack in the frame of the tested pipes. The intent is always to develop a correct correlation between the experimental tests, conducted in a laboratory context, and the results of full-scale tests, thus achieving reliable design criteria.

As it is well known, after starting, the crack might propagate at a stationary speed or might gradually stop, according to the general characteristics and ductile properties of the steel used [2,3,4]. With the aim to identify the resistance force that the pipeline is able to counter to the driving force, given by the pressurized gas, instrumented Drop Weight Tear Tests are performed on SENB-shaped specimens [5,6,7]. The output of these tests is the measurement of the energy dissipated during the steady propagation of the crack. Through energy computation, performed with the application of a two ligament method [8,9] or a single test method [10,11], the ductile characteristic of the steel is deduced. The tests are generally conducted in full thickness, on a specimen extracted from the pipe and flattened, so that the results are not suitable to characterize the material, but the pipeline, instead.

The effective conditions of a crack, running on a pipeline, are however not realistically represented by tests, for several reasons [12]. Among others, one aspect regards the actual shape of the fracture front within the thickness that can remarkably affect the results deduced.

In reference [13] it is claimed that the crack inner profile, when stable propagation occurs, presents an internal development which is self-similar; the profile of the fracture moves in the direction of propagation with only minor modifications of its shape.

Indirect measurement of the Crack Tip Opening Angle is generally adopted to correlate the DWT Tests with Full Scale Burst experiments. According to all proposed models, the three dimensional development of the fracture is averaged on the thickness. The crack tip is identified by a unique representative value, regardless of the specimen thickness. According to this simplified assumption, the residual ligament value is set, and a direct kinematical method for the fracture progression is applicable [14].

After the direct observation of fracture profiles, it is well known that the fracture front, even if self-similar, develops in a non-trivial way through thickness [15]. An evident tunneling can be evidenced, interesting an extension that is even higher than the specimen thickness itself.

In previous works, using subsequent frames of images taken during a DWT Test [16,17] the following quantities have been monitored: opening angle of the two halves of the specimen, progression of the crack tip at the specimen surface, effective CTOA value according to model [18], actual Center of Instantaneous Rotation of the two specimen halves during the motion.

The mathematical description of the cast of the fracture is helpful to the determination of an equivalent position of the crack front. Furthermore, it is possible to realize a more realistic 3D mesh for finite element computation, getting an updated value of the ligament, so that the model [14] can be applied in a more reliable form.
The present analysis is performed on two different pipeline steels, classified as X100 and X60, according to the API standards, having 21 mm and 14 mm thicknesses, respectively. The comparison between the two types of steel accounts for the different behavior occurring when the effective stress field is modified. The total energy input into the system by the tensile test machine is computed together with the energies associated with the bending of the specimen and the axial deformation due to the additional horizontal.

2. Considerations on DWT Test as a method to evaluate a pipeline steel

There are many reasons that make the fracture development in a pipeline different from fracture experienced in a DWT Test. Apart from average crack speeds that are obviously very different, the regions, where the crack tips develop, are interested by non-matching stress and strain fields. The plastic zone ahead the crack tip in pipelines extends even more than a pipe diameter, especially in the longitudinal direction. The nominal stress field is remarkably biaxial in pipelines, while bending in DWTT causes only a one-dimensional stress field. Fracture development inside thickness (surface tunneling) can be different due to crack speed and multi-axial nominal state of stress. Local necking may be also different. Finally, a remarkable effect can be played by the plastic compression induced by the hammer, before the crack starts to grow in a DWTT.

Considering the constraint effects, some solutions have been presented [19,20]. However, no proposal have till now been suggested to modify the DWT Tests so that the stress field result closer to the one experienced by pipelines during crack running. To this purpose, a new layout for conducting laboratory tests on three point bending specimens has been proposed by the authors of this paper [21]. The stress field ahead the crack tip now results as a bending associated with a consistent normal stress. In a DWT Test the stress ahead the tip decreases rapidly, since the nominal stress field is enforced by pure bending. Differently, on cracked pipelines, the nominal circumferential stress is kept on by gas pressure throughout. The actual specimen thickness determines a constrain effect for the fracture, that induces a tri-axial stress field close to the crack tip. The amount of the reduction of thickness should be similar in SENB and in the pipeline, but the effective constraint applied on the crack is also governed by the stress field acting nearby the tip.

It is mandatory to claim that the new layout proposed in [21,22] is not able to reproduce the biaxial nominal state of stress. However, as shown by the experimental measurements carried out with this new set-up, it induces a state of stress ahead the crack tip that allows the crack to propagate in MODE I, with an internal stress distribution that is closer to the one experienced by the pipeline. Of course, like the classical DWT Test, it is necessary to reach stable fracture growth to evaluate the critical parameters of the fracture [14]. This condition is more easily achieved with the new layout proposed. This increases the hope that the critical values of the fracture parameters, identified by the proposed setup, were closer to the effective values to account during a fracture running.

3. The technique to detect the crack profile
In a DWT Test the specimen is broken by means of the energy released by an impact hammer. Generally, the specimen is fully broken. Due to the high test speed, measurement techniques, able to monitor the crack conformation and progression during the event, are not yet accessible. Nevertheless, it is expected that this capability will be available soon, given the rapid developments, both in technical and in economical terms, of the digital optical devices.

In the static experiment it is possible to stop the test when the crack lies inside the region of stable propagation [23, 24] characterized by a stationary CTOA value, then it is possible to attempt the analysis of the crack inner shape.

A mold of the fracture is performed. The mold is formed starting from a liquid silicone resin, with the addition of its catalyst to promote curing.

The extraction of the cast is made possible after complete solidification, but the only way to achieve it is to reposition the specimen on the sliding planes after silicone curing, and complete the test. Within the obtained cast, it is easy to evidence the necking, the surface aspect and the tunneling formed inside the thickness (Fig. 1).

**Figure 1:** Silicone cast of the inner fracture and its digital model

The digital description of the surface of the fracture needs, to be completed, the application of a reverse engineering technique [25], such as laser scanning. Here, to get the digital representation of the fracture surface, a tomographic or stratigraphic technique is adopted. This is, in the same time, easy and very cheap. The tomographic technique allows the representation of solids through the overlap of stratified two-dimensional images.

4. **Description of the experimental set-up and the fracture parameters**
The typical set-up of an experimental DWTT is conducted by measuring load versus displacement during the event. If the test is conducted with the help of an instrumented hammer, it is possible to indirectly evaluate the Crack Tip Opening Angle of the fracture during a quasi-stable propagation [12,18].

The new experimental layout presented in [21] is also provided by a digital image recorder that automatically detects the positions of some markers, appropriately applied. The exhaustive description of the digital system of acquisition is given in [16,22]. The description of the test is provided through the computation of a sequence of digital images taken during the advancing of the hammer. The motion of the two specimen’s halves is identified during loading, even if other displacements are acting in the assembly. The plastic deformations of the specimen are concentrated on the ligament, while all other regions almost behave like rigid bodies. Within all pictures every marker is localized and the taken attitudes are also computed.

The system is composed by a tensile test machine, able to perform static as well as quasi-static strength tests. A couple of extensions are bolted on the lateral sides of the SENB specimen, to lengthen the system while lowering the vertical applied load. Four inclined sliding planes (supports) carry two central hinges placed at the ends of the extensions. The attitude of the supports is oriented outwards of the axis of symmetry, so that a traction is induced in the specimen while the vertical load is applied.

Despite the mechanical assembly, the fracture characteristics of the specimen are isolated from the rest; thus, the effects related to the presence of extensions and inclined supports are accounted and embedded in the solution itself.

**Figure 2:** Scenic view of the experimental set-up

In Fig. 2 a scenic view of the experimental set-up is presented. As previously said, on the specimen and the layout some markers are applied, colored with different shades of red. The clearer red markers are located on the non-
moving parts, providing a reference. Two darker red markers are fixed on the moving halves at a considerable distance from the residual ligament; they are placed in an almost rigid region. One darker red marker indicates the hammer displacement. The remaining two darker markers are fixed on the so called “rectilinear bar”, which lays on the hinges. The movement of the bar helps to know the effective positioning of the assembly on the hinges.

With this new experimental layout it is possible to analyze, with high precision, the kinematic behavior of the entire system. The knowledge of the loads really applied on the specimen - in terms of forces and bending moments – and the displacements of all parts of the set-up, makes it possible to compute the energy supplied by the tensile machine to the experimental layout, and the amount of energy involved in the fracture propagation.

Specifically, five types of energies involved in the test are encountered. The first energy computed is the total energy put into the system by the hammer (called $E_{TOT}$), accounted as the product of the load measured at the hammer and its displacement. Then it follows the energy associated to the bending of the ligament section ($E_{Lig}$); this energy is computed through the product of the bending moment, evaluated in the center of the specimen, and the relative rotation between the two specimen halves. This amount of energy is very important because it represents the energy effectively absorbed by the fracture to propagate. However, it must be pointed out that even if the $E_{Lig}$ is the propagation energy associated with the bending of the specimen, it cannot be the only energy involved in the crack process, if other mechanism of damage is present.

Because of the presence of an additional important load that acts in the horizontal direction, an additional work of deformation involving the specimen assembly results; it is mainly concentrated on the bolts joining the extensions. This work, here called deformation energy ($E_{Flow}$), is evaluated by the product of the horizontal components of the reaction forces - originated by the inclined supports - and the increasing elongation of the full system. The variation in length of the assembly is computed by the comparison of the markers applied on the specimen, hollowing out the effect of the rotation due to the bending. At the joints between the specimen ends and the extensions irreversible relative rotations occur. This amount of lost energy is called $E_{EndCon}$, and is computed through the product between the bending moment acting on the joint and the relative rotation.

The last energy taken into account is the overall friction forces that involve into the system ($E_{Frict}$). To compute this absorbed work, a unique friction force encompassing all others is assumed. This force is considered acting at the interface between the hammer and the specimen, and its value is given by the equilibrium of the bending moment by respect to the center of the ligament.

### 4.1 Combined Test

The inclined supports cause very high loads in the horizontal direction. For this reason, some of the tests (involving high slop values) have been subdivided into two phases. The load is firstly applied on non-inclined supports ($\alpha=0^\circ$), until the crack starts to have a stable propagation. After that, the specimen is remounted on the desired inclined supports. This split procedure allows the use of very inclined supports, thus approaching the effective persistent state of stress that is experienced in front of a
crack running on a pipeline. Some Finite Element results show the advantages of the use of differently inclined supports.

In these models, there is no need here to account of the bolted connections, so that the model consists of a specimen as long as 545 mm with a 12 mm initial indentation. The analyses are focused on the persistency of the stress ahead the crack tip; therefore, the tunneling (non-straight crack through the thickness), the process zone (due to increasing damage ahead the blunting) and the crack growth, are all unconsidered.

The results are shown in Fig. 3. Here the normalized stresses along the ligament for five different DWTT inclined configurations (0°, 45°, 60°, 75°, 85°) are shown, together with the circumferential stress evaluated on a full pipeline. This last is computed according to an explicit Finite Element code, suitably developed for this kind of application [14].

**Figure 3:** Stress trend on the ligament for some support angles

The normalization to the effective flow stress does not make it evident the difference due to T-stress in the two models that is, as a matter of fact, present. However, it is clear that the Fracture Process Zone [26,27] of the pipeline (on the order of the thickness value) surely extends on a region of persistent circumferential stress. This happens in the Three Point Bending specimens only if the slope of the inclined supports reaches values well above 60°.

Low angles of supports, until 60°, are not enough to realize the persistent tensile stress on the specimen, and therefore to suitably modify the stress distribution on the ligament. An interesting issue that is discussed hereinafter concerns the different behavior of steels characterized by dissimilar API grades. These differences become evident especially when high inclinations of the supports are imposed. These differences are observed in terms of shape and attitude of the fracture, as well as in
the energies involved in the fracture process. All these issues will be deeply discussed in the following sections.

5. Comparison between the steels X60 and X100

In the following a comparison between two steels used to realize tubes for buried pipelines, the X60 and X100 will be carried out. The analysis of performances of these two materials is found on data experienced by the DWT tests performed in quasi-static conditions. Silicone fracture casts drawn from the same specimens used to perform the three point bending tests are compared. The comparative study of data obtained from the tests has shown a marked difference in sensitivity by respect to the persistent state of stress state recreated with the new test device. This difference of feeling to the additional stress can be clarified after the analysis of the solid mathematization models of silicone casts and the balancing of the relative energy data.

5.1 Comparison of the fracture attitude of the two examined steels

The resin casts and their 3D digital representation have been performed on two specimens, API X100 and API X60, which both have been tested with two different inclinations of the supports: 0° and 75°. The specimens are also characterized by different thickness that is 21 mm for X100 and 12 mm for X60. The casts are extracted from interrupted tests, which have been stopped when the crack is within the condition of stable growth. The method used to evaluate the critical CTOA makes no difference for the two cases. Fig. 4 shows the digital reconstructions of the casts for the two materials reviewed. There are evident differences in the aspects of the two tunneling shapes whatever the inclination of supports considered is. The first steel presents a much wider extension in depth. Another important aspect regards the amount of necking, much more evident for the first steel, even if it is characterized by a higher thickness. The necking is close to 35 % for the X100 steel and 16 % for the X60.

With the aim to have an insight of the tunneling (and CTOA) on different specimen depths, sections of the digital fracture shapes have been performed on some orthogonal planes. The first plane considered is in the middle of the specimen thickness; the other planes are shifted from this middle plane of a fixed quantity, indicated in the captions of Fig. 5-6-7-8. The CTOA angles come from a fitting extended on the closer points, signed in red in the pictures.

Next Figs. 5-6-7-8 were made symmetric before their representation, by respect to the middle plane of fracture.

The lines represent the tangent to these points. One can see that this angle remains fairly constant for the X60 - 12 mm (Fig.7-8), while in the case of X100 - 21mm it varies more appreciably. In the projection plane d) of Fig.5-6, where it reaches the highest value, it corresponds to the angle emerging from the sample. This measured value is in close agreement with the measurements taken by the picture of the specimen under tests, as indicated in [4]. Concerning measured CTOA values, the direct comparison of the two steels, make it evident an important deviation of the values in the core or in the surface, for the X100. The surface angle is particularly high, in accordance with the optical measurements, but however much higher than the CTOA angle measured inside the specimen thickness. Another important consideration concerns the location of the crack tip, inside the specimen thickness.
Comparing to thickness, the difference between the inner location of the tip and its outer location - for both configurations of test device - reaches 0.810 for the X100 but only 0.375 for X60. These last values indicate that the appearance of the crack in the surface of high strength materials gives only a very approximate location of the crack inside the specimen. If the fracture tip, inside the specimen, extends considerably forwards by respect to surface appearance, it results that the stress reduces considerably because of the linear decreasing nominal stress value.

It is fair to notice that the different depth of fracture indentation of X60 may be related to a lesser thickness compared to X100, rather than to a different material behavior. This aspect will be deepened in the following sections, where trend of energy absorbed during the test will show that the additional constant stress effectively modify the mechanisms of fracture propagation. Another interesting aspect is that different inclinations of the supports, which involve a more persistent state of stress in the specimen, do not influence significantly the values and trends of detected CTOA and depth of indentation of the fracture. A little difference that is possible to note is the more regular edges of the casts obtained from tests conducted with high inclination of the guides.

**Figure 4:** Digital model of the fracture for the X60 and X100 specimen tested with 75° of support inclination

This regularization of the fracture shape is justifiable if considering that the additional constant stress softens the stress field that acts on the crack tip, which would otherwise be the classic one that would originate from pure bending. Considerations, connected to this phenomenon, are discussed by some authors, who claims that the $r^*$ accounted when dealing with high strength steels should be properly increased. At
which amount this increase should be attributed to material characteristic if not to crack tunneling remains a subject still under investigation.

**Figure 5:** Projections of the fracture profile of X100 – 0° steel by planes distinct from middle plane: a) 0mm b) 2.25mm c) 4.5mm d) 6.75mm
Figure 6: Projections of the fracture profile of X100 – 75° steel by planes distinct from middle plane: a) 0mm b) 2.25mm c) 4.5mm d) 6.75mm
Figure 7: Projections of the fracture profile of X60 – 0° steel by planes distinct from middle plane: a) 0mm b) 2.25mm c) 4.5mm d) 6.75mm
Figure 8: Projections of the fracture profile of X60 – 75° steel by planes distinct from middle plane: a) 0mm b) 2.25mm c) 4.5mm d) 6.75mm
5.3 Effect of inner crack profile

It is now clear that the fracture tunneling develops in the thickness in a three dimensional shape. Although, the kinematic models [10,12] all accounts of a 2-D
fracture propagation. In practice, they average the tunneling on a unique front. This simplification can be still adopted, but an equivalent position of the fracture able to match the 3-D solution must be found.

**Figure 9:** Meshes for MODEL 1 and MODEL 2

![Meshes for MODEL 1 and MODEL 2](image)

The typical shape of load-hammer displacement and ligament curves are represented in Fig. 10. To correlate experiments, f.e. MODEL 1 and f.e. MODEL 2, a reference condition is considered (imposed displacement, fracture surface position, applied load).

The first comparison (Tab. 1) shows the excellent overlapping of the experimental condition and the results given by MODEL 1. In synthesis, by imposing the same displacement, the same applied load results. On the contrary, the results performed by MODEL 2 deviates considerably from the experiments.

To this goal, two fem 3-D models have been developed (Fig. 9). The first one concerns the mesh when all the elements inside the tunneling volume have been removed. According to the hypothesis of self-similarity of the crack during propagation, the element erasing is known if one applies the superficial appearance of the crack as monitored by experiments. The second mesh is the simple extrusion of the 2-D representation where the crack tip position is given by its surface appearance.

**Figure 10:** Hammer load- displacement and ligament curves of X100 test
If one pretend to apply the 2-D kinematic models given in [10,12], it is necessary to get an equivalent tip location from the point of view of specimen compliance. Subsequent MODELS 2a-h is similar to previous MODEL 2 but the tip is moved towards the inner tip location of the 3-D model. The compliance results show that an excellent agreement can be found for MODEL 2d. Here the crack tip is in a position intermediate from the location on the surface and the inner tip. This is not the only point of interest. The second one regards an important parameter used in DWTT data interpretation. This parameter is called $r^*$ [28] and reflects the instantaneous center of curvature of the two specimen halves during relative motion, by respect to residual ligament. If one calculates the $r^*$ taking into account of the surface location the $r^*$ shows very high values for X100 if compared to less high strength steels. But if one computes the same parameter considering the effective crack location (MODEL 2d) the $r^*$ value fall inside the same range experienced with non-high strength steels. This means that the tunneling is the cause of this shift discussed in the previous section.

**Table 1:** Comparison among different Finite Element MODEL results
<table>
<thead>
<tr>
<th>Model</th>
<th>Load [kN]</th>
<th>Tip position [mm]</th>
<th>$r^*$</th>
<th>$r_{\text{effective}}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22374</td>
<td>47-60</td>
<td>0.6606</td>
<td>0.5313</td>
</tr>
<tr>
<td>2</td>
<td>42098</td>
<td>47</td>
<td>0.3103</td>
<td>0.5005</td>
</tr>
<tr>
<td>2a</td>
<td>27638</td>
<td>53</td>
<td>0.5967</td>
<td>0.4431</td>
</tr>
<tr>
<td>2b</td>
<td>25524</td>
<td>54</td>
<td>0.6131</td>
<td>0.4657</td>
</tr>
<tr>
<td>2c</td>
<td>23472</td>
<td>55</td>
<td>0.6294</td>
<td>0.4882</td>
</tr>
<tr>
<td>2d</td>
<td>21520</td>
<td>56</td>
<td>0.6453</td>
<td>0.5102</td>
</tr>
<tr>
<td>2e</td>
<td>19644</td>
<td>57</td>
<td>0.6620</td>
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</tr>
<tr>
<td>2f</td>
<td>17808</td>
<td>58</td>
<td>0.6778</td>
<td>0.5550</td>
</tr>
<tr>
<td>2g</td>
<td>16088</td>
<td>59</td>
<td>0.6943</td>
<td>0.5778</td>
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<tr>
<td>2h</td>
<td>14443</td>
<td>60</td>
<td>0.7106</td>
<td>0.6004</td>
</tr>
</tbody>
</table>

Even simply adopting MODEL 2, considering the effective position of the crack tip (2d), it is very interesting to show that the IRC measured during an infinitesimal unloading of the specimen again indicates the solution d as the best representative of the 3-D model.

The final interpretation of all this results is that one can still adopt the 2-D model, thus taking advantage of the simplified kinematic model of the DWTT, but only after an optimal positioning of the crack tip ahead the surface appearance, and accounting of the measured tunneling.

6. Evaluation of X60 and X100 performances

The different orientation of the supports determines a modification on the kinematics of the test. In the standard DWT Test the specimen is hold on by two rigid hemi-cylindrical contact surfaces. In the present experimental set-up the specimen is hold on two circular hinges centered on its middle height that can move on inclined supports.

As above mentioned, it is suggested to analyze the experimental results by using the relative rotation of the specimen halves rather than the vertical displacement of the hammer.

To this regard, it is useful to analyze the results given in Figs. 11-12, which show the hammer load versus relative rotation of the specimen halves for five slopes of the inclined supports: 0°; 22,5°; 45°; 60° and 75°. The combined test methodology has been used only for the X100 specimens with 60° and 75° inclination angles. Fig.11 refers to tests carried out on X100 SEN-B specimens with 21 mm thickness and 25 mm of initial indentation, while Figs. 12 refers to X60 SEN-B specimens with 12 mm thickness and 25 mm of initial notch. In Fig. 11 the plotted curves are all characterized by the same peak load, but their shapes are not overlapped. In the same figure, a principal family of curves can be single out: supports angles (0°; 22,5°; 45°; 60°). The curve related to the highest inclination, instead, shows a trend that deviates from the previous ones. This unevenness is connected not only to test typology (combined test), which explains the concentrated discontinuity in the graph, but also to the intensity of the applied horizontal forces, that are much stronger than 60°. As a matter of fact, the magnitude of axial load is proportional to the tangent of the angle. The comeback of the load that occurs shortly after the above mentioned discontinuity - which corresponds to a very high energy absorbed by the system - is
due to an effective opposition of the specimen to crack propagation. It is interesting to notice that in the 60° case this behavior was not absolutely discernible. Up to 60° the effect of the stress persistency is not remarkable, that is to say that the work of fracture is not affected by the slope itself.

The increased resistance to propagate crack experienced in Fig. 11 is not found in the trends of Fig. 13, where the residual Ligament versus hammer displacement are proposed.

**Fig.11-12: Trend of Hammer Load for X100 and X60**

**Fig.13-14: Trend of fracture advance for X100 and X60**

Here we can note how the fracture accelerates, consuming the entire ligament with 20% less of the hammer displacement by respect to the other tests. The crack, to increase its speed, needs that the available *driving force* grows in the system. This
The effective bending momentum, evaluable as propagation energy, is correlated with the effective bending momentum acting at the ligament section. In Fig.15 the effective bending momentum is shown.

**Fig.15-16:** Trend of bending momentum for X100 and X60

With the higher inclinations of the supports, it is expected that all forms of the irreversibility increase their intensity. In fact, looking Fig.21-23-25, we can observe that the energies associated with the horizontal elongation of the assembly and the work done by the overall friction forces increase, but their sum is far to match the $E_{Tot}$ value. Again, in the 75° slope, after the discontinuity the trend shows a soft
comeback in the last part of the test, while the value of the bending remains steady in region corresponding to the stable growth condition. This suggests that the energy associated with the bending of the specimen - we consider it as the principle supporter for the fracture propagation - is comparable with the other inclinations. In Fig. 17 the $E_{\text{Lig}}$ versus actual ligament are plotted. For the highest inclination of supports we notice that the energy is superimposed on the others trends (slightly higher in the first part of the test). This assertion indicates that the energy involved in the fracture process, which caused the acceleration of the crack, is not effectively supplied by the bending. The trend of the total energy of the system (Fig. 19) remarks that the tensile test machine made more work to perform the test, even if the additional amount of energy is concentrated in the final part of the experiment.

Fig.19-20: Trend of $E_{\text{Tot}}$ for X100 and X60

This energy unbalancing, in part, validates the assertion that the surplus of work made by the hammer has been involved in the propagation, and underlines that the bending is not the only mechanism that supports the crack growth. Probably the fracture propagation is favored by the consistence of the stress due to the elevate force induced by the supports, that allows to reach an extended plastic flow in the region located ahead the crack tip. This wide plasticity is accompanied by a substantial outlay of energy that does not influence the bending, as if it were overlapped on this last one.

In other words, the energy effectively used for fracture advance seems only little influenced by the persistent state of stress; although an overall increased energy is measured as the consequence of an increased plastic flow. Fracture energy balance is similar whatever the sliding angle is, but the crack speed versus hammer advance is increased. I.e. the fracture mechanism increases its intensity but decreases its extensive parameter. This could provoke a running speed higher than expected by the analysis based on classical DWT Tests.

A partial endorsement to the above consideration can be found by coming back to the silicone cast comparison (0° - 75° for X100). The inner CTOA - dominated by
fracture damage decreases if a 75° slope is applied, while the surface CTOA - more affected by the diffusive plastic flow - increases for the 75° slope.

**Fig. 21-22:** Trend of $E_{\text{Flow}}$ for X100 and X60

**Fig. 23-24:** Trend of $E_{\text{EndCon}}$ for X100 and X60

This assertion is indirectly endorsed by full scale burst tests, where X100 behaves in an uneasily predictable way, basing on simple fracture analyses. The principal models used to evaluate the fracture parameters do not take in account that the pipeline nominal stress field ahead the crack tip is very different from that experienced in a DWT Test. Furthermore, the nominal stress involved by the pure
bending in DWT Test is also influenced by the short extension of the ligament, accentuating the stress amplification at the notch. Completely different situation occurs for the tests performed on X60 specimens. In Fig.12 peak load of trend referred to 75° of inclination supports is lower than the others, as if the specimen was less resistant. This difference of load is remarkable, and it is established at the 14%. Also the bending momentum is more feeble, but less remarkable than the hammer load (see Fig.16). A smaller load and bending momentum at ligament section suggest that the fracture propagation has occurred with a lower speed. But Fig.14 denies this assumption, showing that the all trends are superimposed. In other words the fracture is propagated at the same velocity of the other cases, but it requires less energy.

**Fig.25-26: Trend of** $E_{Frict}$ **for X100 and X60**

In Fig. 18 the trends of the $E_{Lig}$ confirm the above assertion. It is evident that in the X60, at the contrary of X100, the process of fracture propagation changes if a consistent additional stress is introduced. In the X100 this stress, characterized by high intensity, activates the residual resistance of the material, otherwise unused by the pure bending. In the X60, instead, consistent additional load distribution tends to overthrow the *resistance force* that the specimen should explain.

6. Conclusion

The paper deals with a modification of the DWT Tests performed on full thickness specimens taken from pipelines. The objective is to arrange the test so that the stress field in the region, where the crack develops, maintains its value as it occurs on pipelines. The advantages of this new set-up are discussed in the paper. The adoption of extensions on the specimens allows the reduction of the compression plasticity under the hammer, which generally reduces the usability of the results.
The influence of crack tunneling in the DWT Tests, used to introduce criteria for crack propagation, is also discussed. All the methods generally adopted, make use of the energy dissipated during crack advance. In this context, the effective crack tunneling can modify significantly the results, as shown in the paper. A method to get a measurement of the crack tunneling is presented. The method was applied to have a realistic modeling of the phenomenon through finite element analysis.

In the paper, the comparison between two pipeline steels, X100 and X60, showed that important differences occur when the stress field is changed by modification of the inclined slopes: X100 increases its plastic flaw features, X60 decreases its fracture resistance.

Note that the results refer to quasi-static tests. It is clear that fracture tunneling under dynamic conditions may change, but the method here presented and discussed could be extended to dynamic tests too.

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