# X100 - FRACTURE INITIATION AND PROPAGATION

G. Mannucci – Centro Sviluppo Materiali S.p.A, Rome, Italy
G. Demofonti – Centro Sviluppo Materiali S.p.A, Rome, Italy
M. Di Biagio – Centro Sviluppo Materiali S.p.A, Rome, Italy

## ABSTRACT

A series of important projects aimed to investigate the suitability of X100 grade steels for high pressure pipeline use have been carried out in the recent years. The worldwide recognized opinion is that X100 steel pipes are nowadays industrially producible and their use has been demonstrated to be economically viable too, but limitations might occur to their application if important aspects related to their structural reliability are not fully clarified. One of the essential points deals with the general fracture properties of these ultra high strength line pipe materials, like defect tolerance, ductile to brittle transition and fracture arrest capability.

In this paper a few CSM results/experiences gained in the recent past [7, 8] about the general fracture behaviour of X100 steel grade large diameter pipes (including defect tolerance, ductile to brittle transition and ductile fracture arrest capability) are reviewed and discussed.

## KEYWORDS
HIGH GRADE; FRACTURE INITIATION; DUCTILE TO BRITTLE TRANSITION; FRACTURE PROPAGATION; HIGH GRADE STEEL MATERIAL; CRACK ARRESTOR; TOUGHNESS.

## INTRODUCTION

Large diameter pipes in X100 steel grade or even higher are nowadays industrially producible and their use has been demonstrated to be economically viable for the construction of long distance gas transmission pipelines [1] [2] [3] [4]. Nevertheless limitations might occur to their application if important aspects related to their structural reliability are not clarified and understood in depth: one of the essential points deals with the general fracture behaviour of these new materials, like defect tolerance, ductile to brittle transition and fracture arrest capability.

As far as the general fracture behaviour of steel pipes for gas pipeline is concerned, early research works in the USA and Europe (especially conducted at the Battelle Memorial Institute [6] in the '70) resulted in correlations established between fracture appearance in small-scale test pieces and fracture parameters measured in full-scale tests. Following those works it became usual to require a minimum shear fracture area percentage, typically 85%, for a Battelle Drop Weight Tear Test (i.e. the so-called Battelle 85% SA criterion) carried out at a specified temperature, in order to avoid the brittle crack propagation occurrence on pipe material, and a minimum Charpy energy value to avoid failure by unstable ductile fracture propagation (stated by semi-empirical approaches as the well-known Battelle Two Curve method). At the same time the criteria for assessing the resistance of steel linepipes to initiation of fracture from axial defects were established once again basing on historical Battelle works.

Moving to more recent years appeared evident that the range of applicability of all these methods was limited by the experimental database used to establish the relevant equations and, at the same time, it is now quite recognized that they could be inadequate to characterize fracture resistance in modern high strength-high toughness linepipe steels as for the X100 case. So fracture behaviour of these new materials lies outside the field covered by the existing experimental data and hence extrapolation is possible but not reliable: to extend the application field of the empirical models devoted full-scale and laboratory test programmes have been made by many R&D Centres supported by Industries and/or Authorities, such as ECSC (European Coal and Steel Community) and EPRG (European Pipeline Research Groups) from '90 ([6], [7], [8], [9], [10] e [11]).

In this paper a few CSM results/experiences gained in the recent past about the general fracture behaviour of X100 steel grade large diameter pipes are presented; in particular the results obtained by CSM in two major European funded projects [7, 8] are reviewed and discussed. They deal with defect tolerance behaviour from axial surface defects, ductile to brittle transition at very low temperature and ductile fracture arrest capability, the latter obtained either by self arresting material or external mechanical devices (i.e. crack arrestors).

## DEFECT TOLERANCE REQUIREMENTS

Criteria for assessing the resistance of steel linepipes to initiation of fracture from axial defects are well established, although based on semi-empirical approaches. In this context, the most considered and widely used are the Battelle formulas [5], also referred to as the NG-18 equations [12] subsequently revised in the early 1990's in the ductile flaw growth model [13], which are presented in a flow stress and a toughness dependent form. It is historically assumed that for pipe material with Charpy-V toughness levels above 40 Joules, fracture initiation is flow stress dependent. When the bursting behaviour is flow stress dependent the criterion for the failure of the pipe containing a surface flaw is given by the well-known Battelle formula (equation 1).

$$\frac{\sigma_f}{\sigma_0} = \frac{1 - d/t}{1 - d/(M \cdot t)}$$

Equation 1 – Battelle flow stress dependent formula

where:
$\sigma_f$ = failure stress; $\sigma_0$ = flow stress; d = defect depth; t = wall thickness;
M = Folias factor, which accounts for stress amplification at the ends of the flaw resulting from outward radial deflection along the flaw.

Several formulas can be found in the literature for both the flow stress and Folias factor. It was demonstrated [32] that for conventional steel grade pipes there is not relevant influence on the overall accuracy of the Battelle equation in choosing a particular Folias factor definition among those available. The same was demonstrated for the flow stress definition. Even if the same has to be still proved for the X100 case, it is reasonable to expect a similar less influence. The selected couple of flow stress and Folias factor expressions are reported in eq. 1 and 2:

$$\sigma_o = (YS + TS)/2$$

Equation 2 – Flow stress
(YS=yield strength, TS=tensile strength)

$$M = \sqrt{1 + 0.4025 \cdot \left(\frac{2C}{\sqrt{Rt}}\right)^2}$$

Equation 3- Folias factor
(2C=defect length, R=pipe radius)

The Battelle formula was developed and validated basing upon full-scale tests on different classes of pipe steels with a maximum value of yield to tensile ratio equal to about 0.87 and a Charpy V toughness in the range 30 to 130 J. However, only a negligible fraction of these refers to high-grade steels (>X70) and no data exist referring to "modern" low-carbon TMCP ultra high-grade steels (> X80). Such high grade steels shows high toughness (>200J in terms of CharpyV upper shelf energy) but at the same time high values of yield to tensile ratio (>0.93) due to the lower values of both strain hardening exponent and uniform elongation if compared with lower grade steels; it results in a limited capability to distribute plastic deformation far from the defect zone, thus lowering the failure pressure as a consequence.

An investigation of the behaviour of such a class of ultra high strength steels in presence of axial surface defects is strategically relevant to check if existing plastic failure criteria are still applicable. In recent years specific studies have been carried out on this topic, and some test data on X100 steel pipes [14] tends to demonstrate that conventional predictive formulae can be also used to safely predict the failure for X100 pipes as good as for lower grade steels data, even if slightly lower conservative predictions were found for pipes exhibiting higher Y/T ratio. In particular, several full-scale activities were performed by CSM to evaluate the defect tolerance requirements to prevent initiation of fracture from axial surface flaws in base material. Four hydraulic tests on single pipes on both geometries (56"x19.1mm and 36"x16mm) with machined axial surface defect with different length/depth ratio were carried out. All the tests were accomplished at room temperature, filling the samples with water (100%) until failure occurred.

The mechanical properties (tensile data on round bar not flattened specimen, transverse orientation) of the tested pipes together with the main test conditions and results are reported Table 1.

| Pipe size (OD x WT) | 56"x19.1mm | 56"x19.1mm | 36"x16mm | 36"x16mm |
|---|---|---|---|---|
| Pipe n. | 846077 | 846014 | 99457 | 99457 |
| Yield strength Rt0.5 (MPa) | 740 | 795 | 739 | 739 |
| CharpyV shelf energy (J) | 261 | 171 | 253 | 253 |
| Y/T ratio | 0.96 | 0.95 | 0.91 | 0.91 |
| Defect length 2C (mm) | 180 | 385 | 150 | 450 |
| Defect depth d (mm) | 10.4 | 3.8 | 9 | 6 |
| Experimental. burst hoop stress (MPa) | 567 | 712 | 670 | 597 |

Table 1 – Defect tolerance test conditions and main results [14]

In Figure 1 the comparison of the present X100 results on both pipe geometries (56" and 36" OD) is presented, with the available CSM database of burst test results on lower grade steel pipes with longitudinally oriented V shaped machined surface flaws and Charpy-V toughness above 40 Joule.

The main result coming from Figure 1 is that the Battelle formula well predicts the failure stress value of X100 pipes with a slightly higher conservative level for the 36" pipe geometry, which is associated with a lower Y/T ratio.

In general the capability of the Battelle equation to correctly predict the failure for the X100 tested pipes is as good as for lower grade steels data. So, despite the low number of testing evidences provided so far on this topic, it seems that the expected detrimental effect due to the reduced strain hardening capability of X100 line pipe materials does not seriously affect the reliability of current predictive defect tolerance requirement criteria, and therefore this point could not represent one of the most critical to be faced in the near future for demonstrating the full reliability of this new class of high strength line pipe materials.

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Despite of such promising results, the issue of the actual influence of the reduced strain hardening capability of this new class of high grade steel on the structural integrity resistance of the line deserves further investigation. A series of questions linked to construction, mechanical design, steel and welding specifications, working factors in relation to pressure containment and bending deformability, geohazards etc.., are in fact still open, being one of the major concern the pipeline structural integrity, in service over the envisaged life span (min.30 years), in real environment (see paper [33] presented at this Conference).

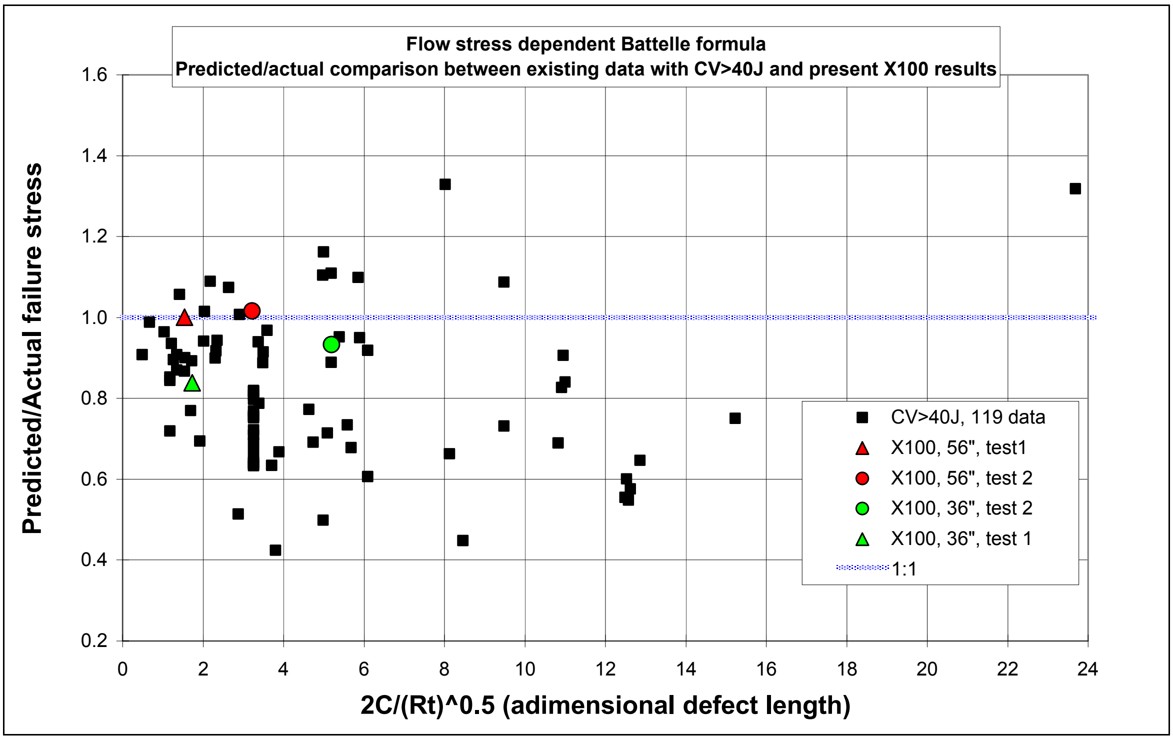


Figure 1 – Comparison of the present X100 results with the available database [14]

## DUCTILE TO BRITTLE TRANSITION TEMPERATURE

The philosophy followed so far by the gas companies in order to avoid brittle fracture is to ensure that the operating pipeline temperature is higher than the ductile-to-brittle transition temperature of the pipeline steel. In fact the brittle fracture can be arrested only at very low stress levels, the only acceptable approach used by the gas companies for controlling brittle fracture propagation is based on the specification of a minimum toughness requirement to ensure that brittle fracture does not occur. In practice brittle fracture propagation is prevented by specifying a minimum toughness to ensure that the linepipe steel is on the upper shelf of the toughness transition curve at the minimum operating temperature.

Experiments carried out since the 1970's [6] show that a correlation exists between the percentage shear area (and the transition temperature) of a Drop Weight Teat Test (DWTT, [15]) specimen and the full-scale linepipe; the fracture propagation transition temperature on pipe material is normally taken to correspond to the temperature at which a DWTT specimen exhibits at least 85% shear area fracture (Battelle criterion). This requirement ensures that the linepipe steel cannot exhibit brittle fracture behaviour in full-scale conditions. The 85% Shear Area (SA) Battelle DWTT criteria was introduced in the EN 10208-2 standard [16] and has been widely used throughout the world since. Therefore, the temperature corresponding to ductile fracture behaviour of a pipeline is usually fixed to be the one at which the DWTT percent shear area is 85% of the evaluated fracture surface.

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Over the last years this approach was confirmed [17] also for large diameter pipes with mechanical properties corresponding to steel grades from API X65 to X80, and high thickness (26 to 38.1mm); a fully experimental confirmation for X100 line pipe material is still lacking, even if for X100 steel this was partially filled by some successful West Jefferson full scale tests carried out on X100 line pipes ([7], [14]). A significant example is reported in Figure 2 and Figure 3, where transition curves and fracture appearance, obtained by small scale laboratory specimens, are compared with the West Jefferson (WJ) full-scale test results. It can be noted that the 85% SA Battelle criterion results completely fulfilled and the DWT tests allow the determination of the pipe transition temperature in a conservative way for the X100 material tested.

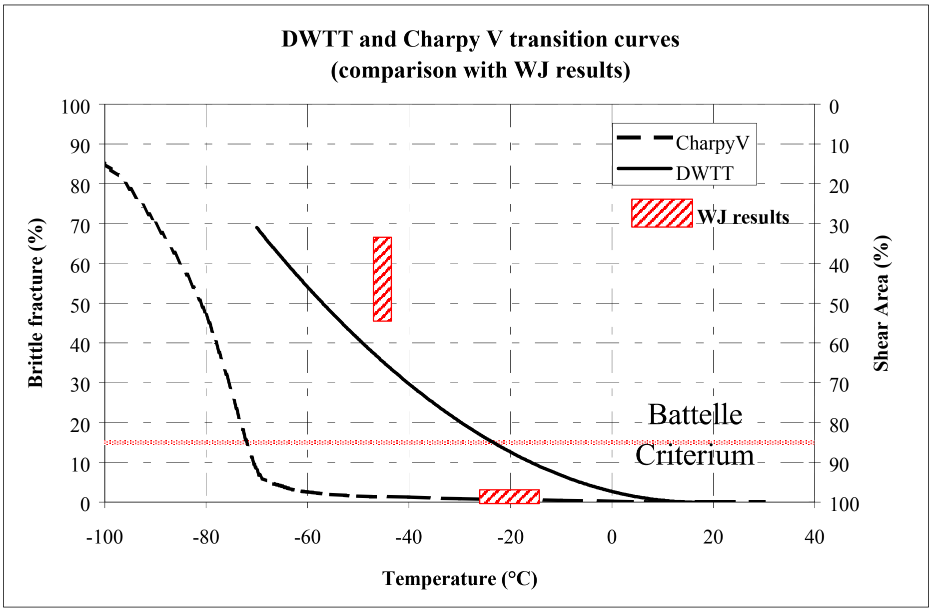


Figure 2 – Comparison between CharpyV, DWTT and WJ test results for an X100 pipe [14]

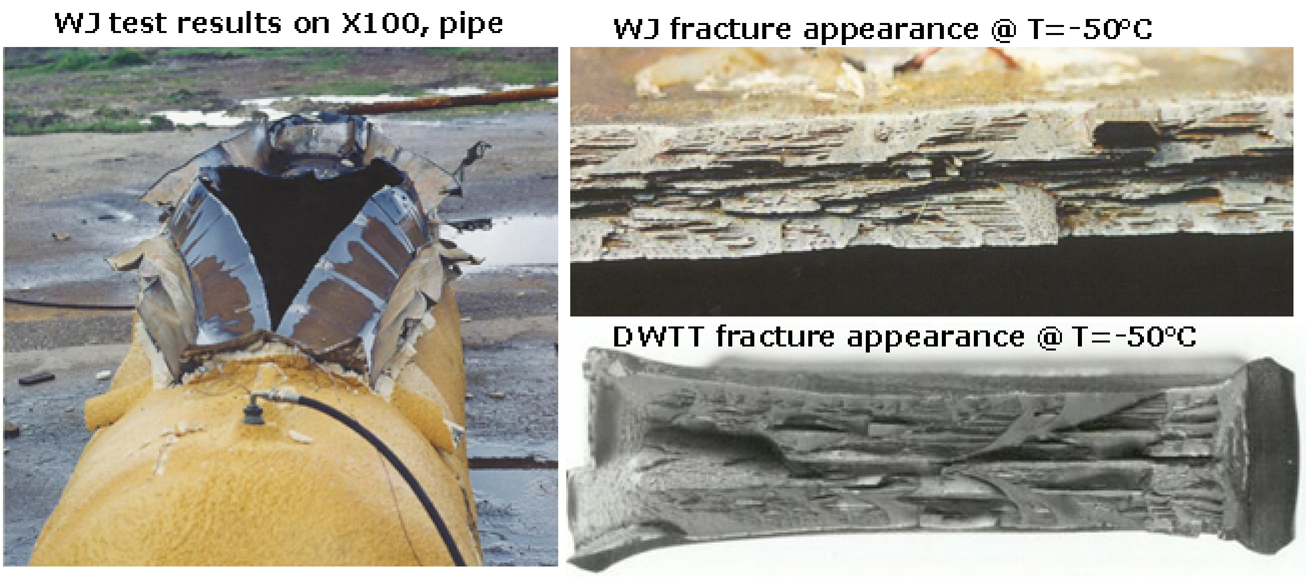


Figure 3 – Comparison between DWTT and WJ test results for an X100 pipe [14]

A potential matter of concern for X100 pipe producers could be on how to guarantee the 85%SA on DWTT specimen at the minimum required temperature, that for some challenging projects located in hostile environment, as in the North - Canada area for instance, is typically down to -20°C and even lower.

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## FRACTURE PROPAGATION CONTROL

The propagation of a fast running shear longitudinal fracture is one of the most serious event, the fracture potentially affecting a long part of the line causing a long and costly gas delivery service breakdown. Fracture propagation control is therefore an extremely important aspect of gas transmission design. The determination of the toughness values required for arresting ductile fracture propagation has been historically based on the use of models in the form of predictive equations, which state the minimum required value of the Charpy upper shelf energy as a function of both pipe geometry and applied hoop stress. These semi-empirical predictive relationships have been developed using a combination of theoretical analysis and available burst test data ([6], [18], [19], [20], [21], [22] e [23]).

In particular the Battelle Two Curve approach [6], is the most appreciated predictive method for medium-high strength steel linepipes so far; it takes into account the decompression behaviour of the pressurising medium used in the test at the corresponding pressure and temperature and it is strongly recommended when high pressure and/or rich gas is involved. Its validation range is restricted so far to the API X80 grade and the consequent level of hoop stress (≤ 400 MPa), and therefore its extrapolation to X100 steel grade operating at very high hoop stress (≈ 550 MPa) is highly questionable; in practice the CharpyV-based methods have proved to be not conservative under conditions outside the range within which were developed.

One way to overcome this problem should be to use an appropriate correction factor, calibrated on the basis of past experimental evidences as close as possible to the situation being evaluated. In practice this correction factor should be “case by case” evaluated, being dependent on the material properties and the test conditions. Nevertheless for X100 case, recent CSM’s full scale burst test results on X100 pipes definitively proved that it is not possible to rely on Charpy-V energy at all and new criteria are needed. Figure 4 shows two photos (burst onset and line after the test) of a CSM’s burst test on X100 steel pipes.

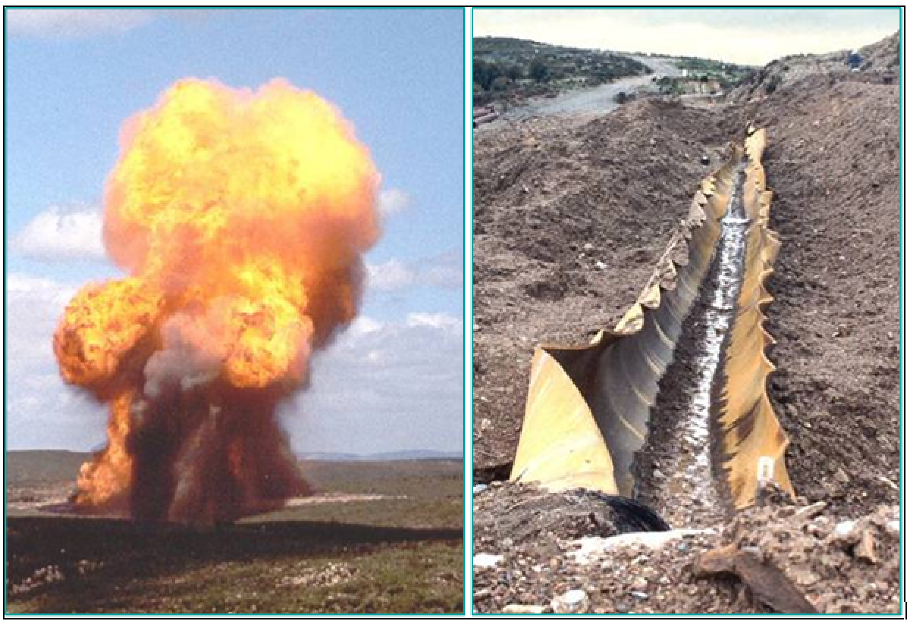

Figure 4 – CSM’s burst test on X100 pipes [23]

This is clearly reported in Figure 5, where arrest and propagation points are depicted in terms of actual and predicted Charpy-V energy; data points in Figure also include burst tests results on lower steel grade pipes (X80) for comparison.

It can be noted that the correction factor of 1.7, formerly proposed by CSM in order to properly correct the Battelle Two Curve arrest predictions [14], does not work any more once a wider X100 data set are considered. In addition it is not possible to derive any new correction factor able to divide propagation from arrest points. In Figure 5 also X120 test data are reported, belonging to the unique full scale burst test carried out on X120 pipes so far (CSM test carried out on behalf of ExxonMobil, [24]); note that in such a test no arrests were observed.

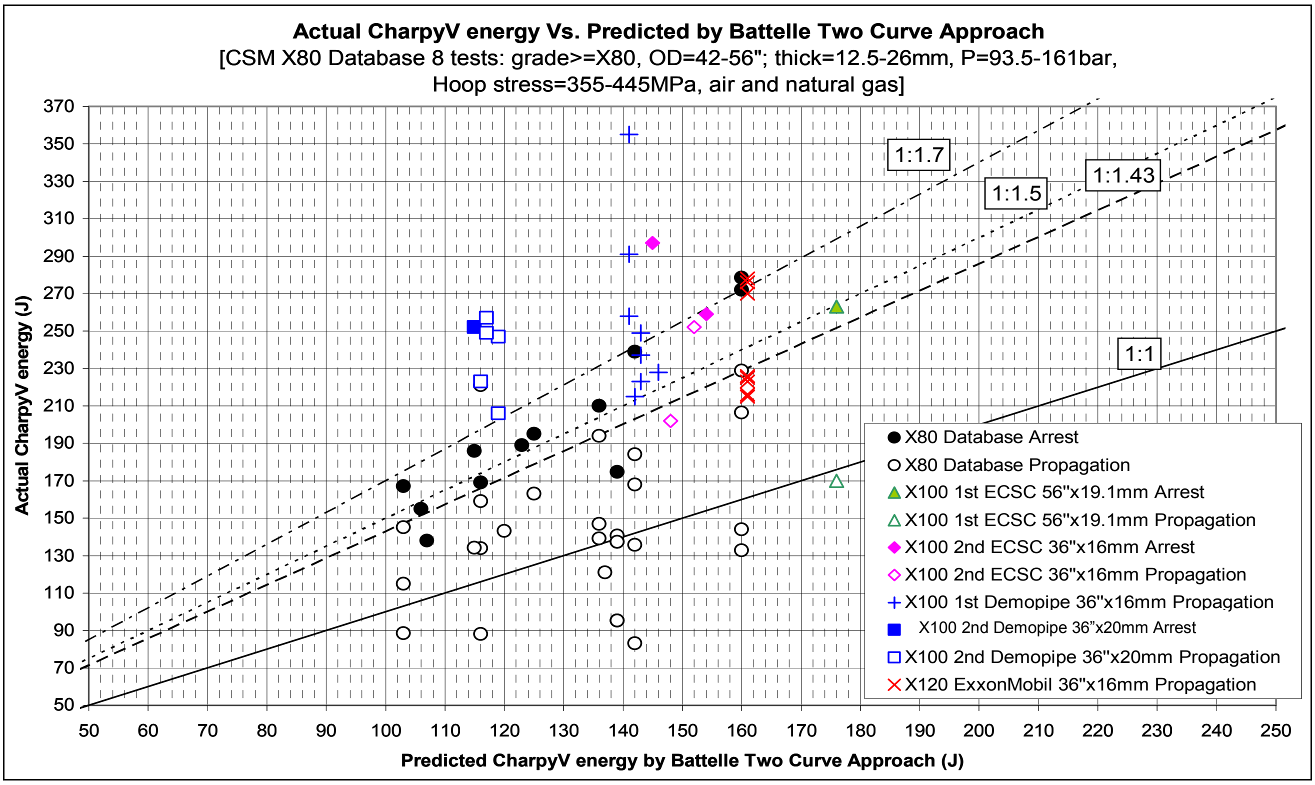


Figure 5 – Actual vs. Predicted CharpyV energy by Battelle Two Curve Approach for high-grade steel linepipes (CSM's database)

Summarising and viewing the results reported in Figure 5, Ductile Fracture Propagation Control (DFPC) for high strength steels is as in the following:

- DFPC is still based upon conventional CharpyV-based criteria with empirical correction factors which are considered to work satisfactory up to X80; for steel grades >X80 such empirical correction factors proved to be unsuitable and to provide unsafe predictions.
- For X100 steel linepipe, actual fracture propagation results demonstrate that such a class of steel really lies on the arrest/propagation border line, actual results (arrest or propagation) strongly depending on the operating conditions (usage factor, type of gas, operating temperature); for the most severe cases external mechanical devices, i.e. crack arrestors, can be necessary and hence required to ensure a safe arrest.
- For X120 steel linepipe it is not possible to rely on pipe body fracture self-arrestability, at least for the operating conditions usually envisaged; use of crack arrestors could be therefore mandatory.

It appears clear that together with a proper metallurgical steel design in order to ensure general good toughness properties, due to the intrinsic material limitation in terms of fracture propagation resistance, gas companies are now forced to be able to proper design and install such additional external devices (crack arrestors) in order to guarantee against an uncontrolled fracture propagation event.

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CSM, which since early 70’s is conducting valuable research efforts on running shear fracture topic, recently developed such a tool in the form of a finite element model (PICPRO®, [31]) able to simulate dynamic ductile fracture propagation, also considering the effect of crack arrestor constraint on the running fracture. Such a model has been successfully used to design crack arrestors for the X100 BP line [25], and more in general its numerical predictions have been compared with the results of recent experimental burst tests carried out on large diameter gas pipelines in steel grade X100/X120 demonstrating the capability of the model developed to correctly predict the crack arrestors performance not only in terms of arrest/propagation behaviour, but also in terms of arrest length/exit propagating fracture speed values.

Figure 6 – Crack arrestor modelling and actual test results on X100 pipes [25]

Finally a short mention to the alternatives to conventional Charpy-V energy-based approaches for ductile fracture propagation control is given here. Generally speaking, a number of alternatives have been explored and developed by several researchers ([26], [27], [28], [29], [30]) since many years. DWTT specimen, being full thickness and longer in ligament, was recognized as one of the most promising specimens for properly taking into account the fracture event, and methodologies adopting similar specimen (as the Crack Tip Opening Angle, CTOA) were hence introduced and studied. In particular the latter, which represents one of the most promising methods for predicting crack arrestability in high strength/high toughness steels, makes use of finite element analysis for deriving information from the applied driving force point of view to be compared with laboratory test data. The use of CTOA as the toughness parameter derives from post-yielding fracture mechanics concept; in practice this approach is based upon the balance between the capability of the steel to resist the crack propagation (expressed by the CTOA critical value of the material, named CTOAc, properly measured in laboratory by a suitable test procedure) and the driving force applied by the external loads (expressed by the CTOA applied, named CTOAa, calculated with a suitable Finite Element Code, as for example the CSM’s PICPRO® finite element code mentioned above).

As a matter of fact, while the capability of FEM tool to predict the actual driving force applied to the running shear fracture on pipe proved to be excellent [31], the test methodology for deriving in laboratory the proper fracture resistance parameter (methodology which was developed and

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validated for lower steel grades) demonstrated to be not fully applicable for the high strength steels of interest. This topic is actually debating, being object of ongoing research programs.

## CONCLUSIONS

This paper presents a brief review of the results obtained in the last years by CSM in the field of fracture properties assessment of large diameter X100 steel pipes for long distance gas transmission lines.

Looking at the results of the extensive full scale testing activity carried out so far on the various fracture related topics, it appears clear that the general fracture behaviour of X100 large diameter pipe resulted to be substantially good, though a devoted “design” is mandatory to prevent/control the ductile fracture propagation event. Concerning specific fracture issues, main conclusions are the following.

The Battelle flow stress dependent formula for assessing the resistance of steel linepipes to fracture initiation from part wall axial defects, correctly predicts the failure stress value even for the high strength, high Y/T ratio (> 0.90 on round bar un-flattened specimen).

The West Jefferson full-scale test results confirmed the validity of the Battelle DWTT 85%SA criterion and the DWT test capability to correctly predict the transition temperature on X100 pipe material.

The Charpy-V shelf energy over-estimates the real resistance to the ductile fracture propagation event of the test pipes at the burst test condition; therefore, also the use of “Charpy-V conventional criteria”, as Battelle Two Curve approach (that it is the most appreciated predictive method for medium-high strength steel linepipes so far; it takes into account the decompression behaviour of the pressurising medium), is highly questionable.

The DWTT specimen, which is full thickness and longer in ligament, was recognized as one of the most promising specimens for properly taking into account the fracture event, and methodologies adopting similar specimens can be useful and promising, but they are still far from a widely validated stage in the range of X100 grade pipes.

The X100 large diameter pipes are working on the upper bound of the arrest / propagation ductile fracture propagation condition, strongly depending on the operating conditions (usage factor, type of gas, operating temperature). Therefore for the more severe cases, external mechanical devices, i.e. crack arrestors, are required to ensure a safe arrest; so in the near future, dedicated work on the use of crack arrestors, as a necessary device to “integrate” the toughness of the base material in terms of the ductile propagation event, must be encouraged.

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