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# INVESTIGATION OF DUCTILE FRACTURE ARREST OF HIGH STRENGTH STEELS FOR GAS PIPELINE APPLICATION

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## ABSTRACT

*The ductile fracture arrest may present supplementary requirement for selection of base material for most demanding steel welded structures. The most representative one with such requirement are gas pipelines. Therefore to ensure that the pipeline materials has adequate toughness to arrest a ductile fracture, the pipe material must be designed and tested in accordance with the specific procedures, such as one specified in ASME B31.8, e.g. supplementary requirements SR5 of API 5L. Actually, the average of the Charpy energy values must meet or exceed the energy value calculated using one of the available equations that have been developed in various pipeline research programs. The paper presents such investigation for selected high strength steels grades for gas pipeline application, while considering the Charpy energy of base metal at various design or testing temperatures.*

**Keywords:** ductile fracture arrest, high-strength steel, toughness

## 1. PREFACE

While world energy demands continuously increasing; needs for production of lighter, safer and reliable, cost-reduced and high-strength materials based structures become particularly important. This can be done primarily by use of high-strength structural materials, which must have higher strength properties, as well as satisfactory ductile and toughness characteristics. While initial faults, approximated as micro-cracks, induced in various ways, may be present in base metal, as well as in weld metal [14], the structural material must have sufficient resistance to crack growth.

Therefore, one of the key concerns in the design of such structures, particularly pipelines, is the avoidance of propagating cracks or fractures. Even the issue of low toughness and fracture resistance has been known for centuries, recent developments of fracture mechanics and sophisticated experimental approaches become more important. Off course, it does not mean that all the issues concerning fracture control are well identified and addressed. In the case of pipelines, new issues arise from two directions. First, new pipeline projects are continually pushing the boundaries in terms of higher design pressures and lower operating temperatures. Second, the new higher strength steels have inherently less ductility and resistance to damage prior to fracturing. An overall approach to fracture control must consider a range of issues including crack initiation and propagation in the parent metal, seam welds, and girth welds. For high strength steels there are particular challenges because the stresses are inevitably higher, which increases the driving force for fracture whilst the toughness, a measure of the fracture resistance, is unlikely to increase to the required extent. In addition, the

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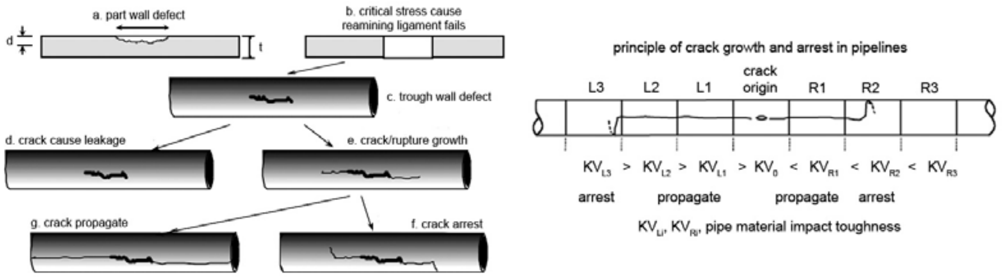
material toughness transition temperature phenomena associated with ferrite high-strength structural steels become also important. However, to control fracture initiation and propagation in the pipe body it is necessary to ensure that the pipe material has sufficient toughness for failure to be dominantly by ductile tearing [4,5,7,8,10].

According to Andrews and Bate (2003) there is a small decrease in tolerable flaw size as the grade increases. However, increasing the pipe grade has a bigger influence on the toughness required to ensure that flow stress dependent behaviour is obtained. For gas pipelines these effects will be over-ridden by the more severe requirements for ductile crack arrest (Figure 1a). On other side, for liquid pipelines where ductile crack propagation is not a concern, these requirements will determine the required toughness. In addition, Andrews and Bate (2003) have claimed that it is neither practical nor necessary to require the seam weld toughness to match that of the parent metal. Gas transmission pipelines are laid with the seam welds offset so that a crack initiating in the seam weld will only propagate for one pipe length. However, some level of toughness is required in the seam weld to give resistance to crack initiation, and this can be set to be equivalent to the level required for flow stress dependent behaviour in the parent pipe [7].



*a) Ductile failure of a defect in a pipeline under pressure loading [Hopkins, 2002]*

*b) Concept of experimental determination of ductile fracture arrest [Higuchi, Makino, 2010]*

*Figure 1. Ductile crack arrest [4,9,12]*

Actually, the crack arrestability of running ductile fracture, RDF, is defined by the absorbed energy of steel. The new concept of crack arrestability of high strength line pipe gives a chance to design high pressure gas pipeline without crack arrestor (kind of mechanical pipe reinforcement), which reduces pipeline construction cost and is expected to reduce gas price in the market [4]. In addition, new consolidated version of pipe specification standard, ISO 3183 and API 5L, are issued as one common specification, where these approaches are well addressed and formulated [2,3].

## 2. AVAIABLE ANALITICAL AND EXPERIMENTAL APPROACHES

A combination of sufficient shear-fracture area, DL [%], and sufficient absorbed energy, KV [J], is an essential pipe-body property to ensure the avoidance of brittle fracture propagation and the control of ductile fracture propagation in gas pipelines. These requirements are set both in gas pipeline design codes, such as ASME B31.8, and pipeline's materials specification standards, such as API 5L / ISO 3834. Generally, the following approaches are applicable [1,2,3,4,]:

$$KV = 0,000267 \cdot \sigma_h^{1,5} \cdot D^{0,5} \quad ...(1)$$

$$KV = 0,000321 \cdot \sigma_h^{1,5} \cdot D^{0,5} \quad ...(2)$$

$$KV = 0,0000357 \cdot \sigma_h^{2} \cdot \left( \frac{D \cdot t}{2} \right)^{1/3} \quad ...(3)$$

$$KV = 0,000357 \cdot \sigma_h^{1,5} \cdot D^{0,5} \quad ...(4)$$

**EPRG guidelines - Approach 1;** this approach is based upon the European Pipeline Research Group, EPRG, guidelines for fracture arrest in gas transmission pipelines: equations from (1) to (3). Required absorbed energy, KV [J], depends on hoop stress, $\sigma_h$ [MPa], diameter of pipe, OD [mm] and pipe wall thickness, t [mm], depending on pipe steel grade (up to L555).

**Battelle simplified equation - Approach 2;** this approach uses the Battelle simplified equation, which is based upon the Battelle two-curve approach. The applicability of this approach is limited to welded pipe, up to L555 grade, and is depended on same variables, $\sigma_h$, D and t. Similarly as for EPRG guidelines, equation (3) applies.

**Battelle two-curve method - Approach 3;** this approach is based upon the Battelle two-curve method, which matches the fracture-speed curve (the driving force) with the pipe toughness or resistance curve. When these two curves are tangent, the minimum level of fracture toughness for fracture arrest is defined. The Battelle two-curve method is described in Pipeline Research Committee International, PRCI, Report 208, PR-3-9113. However, specialist advice should be obtained to use this method.

**AISI method - Approach 4;** this approach is based upon the equation (4), which was statistically fitted to the full-scale burst test data by AISI. The application of this approach is limited up to grades L485 welded pipes.

**Full-scale burst testing - Approach 5;** this approach is based upon full-scale burst testing to validate the arrest toughness for a specific pipeline design and fluid (concept shown on fig. 1b). Typically, a range of pipe toughness, $KV_{Li}$ on “left” side, and $KV_{Ri}$, on “right” side, is installed in the burst test section, with the pipe toughness increasing on each side of the test section as the distance from the fracture origin increases. The KV absorbed energy needed for arrest is established based upon the actual KV absorbed energy of the pipe in which arrest is observed to occur.

## 3. INVESTIGATION ON SELECTED PIPE GRADES

During recent researches, authors have acquired mechanical and production type properties for several gas pipeline steel grades (tab. 1). While all grades are produced by mean of thermo-mechanical rolling, TM, the main difference is in type of cooling cycle; e.g. grades L360-L450 are produced by accelerated controlled cooling, ACC, while L690 is produced by quenching and tempering, QT.

*Table 1. Technological properties of commercial steel pipe grades*

| EN 10208 / ISO 3183 | API 5L | $R_{p0,2min}$ | $R_m$ | A | KV @ +20°C | Standard KV req. | Production type |
|---|---|---|---|---|---|---|---|
| L360M | X56 | >360MPa | >495MPa | >26% | 255J | 40J @ 0°C | TM+ACC |
| L415M | X60 | >415MPa | >540MPa | >28% | 300J | 40J @ 0°C | TM+ACC |
| L450M | X65 | >450MPa | >575MPa | >24% | 280J | 40J @ 0°C | TM+ACC |
| L690QL | X120 | >690MPa | >770MPa | >16% | 225J | 40J @ -40°C | TM+QT |

*Table 2. Design consideration and required impact toughness for RDF*

| EN 10208 / ISO 3183 | Design condition | nominal min. req. t | nominal pipe weight | hydro test hoop stress | EPRG, $KV_{req}$ | Battelle, $KV_{req}$ | AISI, $KV_{req}$ |
|---|---|---|---|---|---|---|---|
| L360M | OD=1219mm<br>$p_D$=70bar | 16,5mm | 495kg/m | 324MPa | 54J | 81J | 73J |
| L415M | | 14,3mm | 429kg/m | 374MPa | 67J | 102J | 90J |
| L450M | | 13,2mm | 396kg/m | 405MPa | 76J | 117J | 102J |
| L690QL | | 8,6mm | 258kg/m | 621MPa | 144J | 238J | 193J |

From the design condition (tab. 2) it may be seen that higher strength grades provides significant weight savings, e.g. up to 48% while comparing L690QL to L360M. However, as can be seen from fig. 2 the best toughness properties posses L415M pipe steel grade, while L690QL has the lowest one. Obviously, the Battelle approach has the straightened impact toughness requirements (tab. 2). Also, grades L360M to L450M have sufficient toughness down to -40°C, while L690QL grade does not have sufficient toughness, even on above zero temperatures (fig. 2). This insufficient toughness for L690QL grade may imply use of crack arrestors on designated areas along pipeline.

Even use of higher grade steel pipeline, such as L690 (X120) offers benefits such low weight and cost reduction, due to the reduced wall thickness, and higher service pressure (for same pipe thickness), the same does not have sufficient toughness to arrest long running cracks.

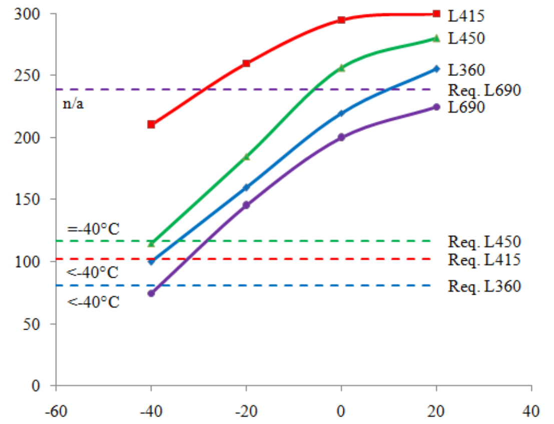


*Figure 2. Comparison of required impact toughness and pipe grades resistance for various testing temperatures*

Those running cracks may be initiated from various pipe manufacturing and pipeline erection faults [9] by further external impact, fatigue, corrosion, earthquakes, landslides, and even pipeline hydro test. According to Bauer, Knauf, and Hillenbrand (2004) such insufficient toughness is even proved by the recent full-scale burst tests on grades X100, where installation of crack arrestors become important pipeline requirement [11].

## 4. FINAL REMARKS AND COMENTS

The increasing pipe strength and pipe diameter of gas pipeline contribute the cost reduction of natural gas. Latest known gas erection projects include pipeline steel grades L555 (X80) up to L690 (X120). While pipeline safety is the first priority, one of the main concerns becomes running ductile fracture, which is a unique mode in high pressure gas pipelines. Therefore, pipeline must be designed to ensure the crack arrest together with crack initiation prevention.

As it is shown, the pipe steel toughness is used to determine the material resistance to long crack propagation, e.g. ductile crack arrest. Determination of required toughness to provide ductile crack arrest is possible by use of analytical approaches (EPRG, Battelle and AISI), as well as by real full-scale burst test. While full-scale burst test requires particular condition, it may be impractical approach for all gas pipeline projects and operators (e.g. clients), and therefore required toughness determination, already in design phase, must be based on existing analytical approaches.

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