The Effect of Hydrogen on the Master Failure Curve of APL 5L Gas Pipe Steels

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Abstract

The effect of hydrogen on the material failure curves of APL 5L gas pipe steels was analysed from viewpoint of the notch fracture mechanics. The material failure curves based on two-parameter fracture criterion have been determined for API 5L X52, X70 and X100 gas pipe steels. The notch fracture toughness $K_{\rho c}$ and the effective T-stress were employed to describe the material failure curve. Tests were carried out on electrolytic hydrogen charged SENT, CT, RT (Roman Tile) and DCB specimens with a notch. Fracture initiation was detected by acoustic emission. Material failure curves for hydrogen charged steels and steels without hydrogen were constructed. It was shown that there is critical hydrogen concentration, which causes significant reduction of local fracture resistance of pipe steels.

Keywords: Notch fracture toughness; effective T-stress, hydrogen; gas pipe steels

1. Introduction

Although there are still numerous questions about the concrete realisation of a possible transition towards a hydrogen economy, hydrogen could play an important role in our future energy supply. Production methods, end-use technologies and storage applications are well known, although there is a need for further research before a real commercial breakthrough can be expected. As far as the transport
and distribution of hydrogen towards the end user is concerned, also further research is still needed, and some practical questions should be addressed.

Pipelines are the safest method of transporting huge volumes of oil and gas. Because many pipelines use corridors adjacent to major highways, railways, waterways and populated areas, safety and pipeline integrity are important international concerns. Experience shows that the majority of pipeline failure initiates from defects or cracks that are either inherent in the material introduced during manufacturing, construction or damage during service [1-3].

To estimate integrity of damaged pipelines, fracture mechanics approach should be used. Constraint effect must also be incorporated into basic equations [4] when it is applied to an in service structure. The notch fracture toughness (critical notch stress intensity factor) \( K_{p,c} \) and the effective T-stress \( T_{ef,c} \) were employed to describe the material failure curve \( f(K_{p,c}, T_{ef,c}) \) [5]. The effect of hydrogen on the material failure curves of APL 5L gas pipe steels was analysed from viewpoint of the notch fracture mechanics.

2. Experimental and numerical procedure

2.1. Materials and specimens

The material used in this study is X52, X70 and X100 steels meeting requirements of API 5L standard.

Specimens of three geometries, namely, CT (width of W=63.80 mm, height of 61 mm), DCB (height of W=45.70mm) and SENT (width of W=58.40 mm) were extracted from a steel pipe of diameter 610 mm. Thickness of all specimens was equal to 5.8 mm. The specimens have a notch with a notch angle \( \phi = 0 \) and a notch radius \( \rho = 0.25 \) mm. To measure the notch fracture toughness of the API 5L X52 steel in radial direction, non-standard curved notched specimens, so called “Roman tile” (RT) specimens, were also used. The details of test set-up of three-point bend test for RT specimens and testing machine with the bend-test fixture are given in Ref. [1, 5]. Test specimen sets include specimens with the initial notch aspect ratio \( a/W \) varied from 0.1 to 0.7.

The specimens are immersed into the cell with solution NS4 and exposed under constant potential of polarisation, which is slightly negative than free corrosion potential for given steel. The hydrogen charging process is controlled by registration of the cathodic polarisation current. Details of hydrogen charging are given in Ref. [1]. After hydrogen charging the specimens were tested.

2.2. Experimental procedure

The tests were carried out at room temperature. Displacement rate was 0.02 mm/s. The test procedure allowed measuring the load corresponding to crack initiation and fracture. Acoustic emission technique has been employed for this purpose. Comparison of dependences of the load versus time and duration of acoustic emission versus time indicates crack initiation and fracture. For this event, acoustic salves with the highest duration and the most important number of acoustic hits are detectable.

Thus, fracture initiation and critical load were detected by acoustic emission to compute the notch fracture toughness and the T-stress ahead of the notch tip by finite element method.

2.3. Numerical procedure

The T-stress is evaluated using finite element method (Castem2000) and computing the difference of principal stresses along ligament for crack initiation and fracture. It was observed that the T-stress is not constant. To avoid dependence of the T-stress ahead of the notch tip, an effective T-stress \( T_{ef,c} \) was
considered and calculated as the average value of the T-stress distribution in the region corresponding to the effective distance \(X_{ef}\)

\[
T_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} T_{ss}(r)\Phi(r)dr
\]  

(1)

The key parameters of the material failure curve, namely, \(K_{p,c}\) and \(X_{ef}\) were derived from the volumetric method of notch fracture mechanics [5].

3. Results and discussion

The \(K_{p,c} - T_{ef,c}\) curve is constructed to create a material characteristic taking into account the effect of constraint due to specimen geometries, ligament sizes, type of steel and loading conditions [5]. To get different assessment points \((K_{p,c}, T_{ef})\), four specimen geometries (CT, SENT, RT and DCB) with several notch aspect ratio were tested.

3.1. Effect of hydrogen charging

Influence of holding time of electrolytic hydrogen charging has been inspired from [1]. The effect of hydrogen charging on the critical notch stress intensity factor for the API 5L X52 steel in the case of CT specimen with \(a/t = 0.5\) is illustrated in Fig. 1. We can note a saturation of the hydrogen embrittlement after 40 days under electrolytic hydrogen charging. The critical notch stress intensity factor for crack initiation decreases by 15.7%.

![Fig. 1. Effect of electrolytic hydrogen charging on the critical notch stress intensity factor for the CT specimen (a/t =0.5) of APL X52 steel](image_url)
To analyse the effect of hydrogen charging on crack initiation and fracture, two fracture toughness parameters, namely, the critical notch stress intensity factor and the effective T-stress of the three steels (X52, X70 and X100) are determined for four specimens (SENT, CT, RT and DCB) with a/t = 0.5 and for constant electrolytic hydrogen charging holding time of 30 days.

3.2. Effect of notch aspect ratio and hydrogen

To get different assessment points \((K_{\rho,c}, T_{ef,c})\), four specimen geometries (CT, SENT, RT and DCB) with several notch aspect ratio were tested. An example of the results of \(K_{\rho,c} - T_{ef,c}\) estimations is given in Fig. 2 for the CT specimens with the notch aspect ratio \(a/t = 0.1; 0.3; 0.5\) with and without the presence of hydrogen. Hydrogen charging leads to the shift of the curve in the region of more high constraint characterized by the value of \(T_{ef,c}\) (Fig. 2).

![Fig. 2. Effect of degradation on the critical notch stress intensity factor and the effective T-stress for CT specimens](image)

3.3. Material Failure Curve \(K_{\rho,c} - T_{ef,c}\)

The material failure curve (MFC) based on the critical notch stress intensity factor \(K_{\rho,c}\) and the constraint parameter \(T_{ef,c}\) has been successfully used to quantify the constraints of notch tip fields for various proposed geometry and loading configurations [5]. We suggest extending the curve of \(K_{\rho,c} = f(T_{ef,c})\) for different steels charging by hydrogen. The results of test for the different specimen geometries with the notch aspect ratio \(a/t = 0.5\) are presented for the case of electrolytic hydrogen charging during 30 days and compared with the results of initial state of the steels.

The experimental assessment points \((K_{\rho,c}, T_{ef,c})\) for four specimen geometries (CT, SENT, RT and DCB) of APL X52 steel are summarized in Fig. 3. These experimental assessment points allow
constructing a material failure curve called also a material master curve which is approximated by the following expression

\[ K_{p,c} = a T_{e,c} + b \]  

(2)

where \( a = -0.0843 \) and \( b = 71.6785 \) for the X52 pipe steel without hydrogen and \( a = -0.0741 \) and \( b = 77.8317 \) with the presence of hydrogen.

The decrease of the notch stress intensity factor with the presence of hydrogen is in the range 5.8 – 9.8 % for the different specimens. The shift between initial value of \( K_{p,c} \) for the SENT specimen and the hydrogenated specimen is small, however a real difference noted in DCB specimen (about 10 %). At the same time, hydrogen charging leads to more high constraint. It should be noted that such behavior of the critical notch stress intensity factor could be interpreted as constraint effect due to specimen geometry, type of loading and hydrogen charging.

Finally, the effect of hydrogen charging on the Material Failure Curve of the X52, X70 and X100 steels is presented in Fig. 4 for different geometry of the specimens after 30 days of hydrogen charging. It can be seen that there is the effect of hydrogen on the Material Failure Curve of these pipe steels.

4. Conclusion

Two-parameter notch fracture mechanics based on the Material Failure Curve in terms of the critical notch stress intensity factor and the effective T-stress has been employed to analyse the effect of electrolytic hydride charging on fracture resistance of the X52, X70 and X100 gas pipe steels. It was shown that electrolytic hydrogen charging as well as geometry of specimens and notch length lead to the shift of the curve in the region of more high constraint characterized by the value of \( T_{e,c} \). This value
could be applied as an important engineering parameter for integrity assessment of pipelines during long-term operation.

Fig. 4. The effect of hydrogen charging on the material failure curve of the X52, X70 and X100 steels

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