The paper was presented at the Eleventh Meeting
"New Trends in Fatigue and Fracture" (NT2F11)
Polignano a Mare, Italy, 3–6 July, 2011

Mohamed Hadj Meliani [1,2], Zitouni Azari [2], Yuri G. Matvienko [3], Abdulrazag Elhoud [4], Guy Pluvinage [2]

FRACTURE ASSESSMENT PROCEDURE OF API 5L GAS PIPE STEELS

POSTUPAK PROCENE LOMA ZA API 5L ČELIKE GASOVODA

Originalni naučni rad / Original scientific paper
UDK /UDC: 621.643: 539.42
669.14-462: 539.42
Rad primljen / Paper received: 21.01.2012.

Adresa autora / Author's address:
[1] LPTPM, FSSI, University Hassiba Benbouali of Chlef, Algeria, hadjmeliani@univ-metz.fr
[2] LaBPS-ENIM, University Paul Verlaine of Metz, France
[3] Mechanical Engineering Research Institute of the Russian Academy of Sciences, Moscow, Russia
[4] Sinal Equipments Scientific & Didactique, Annaba, Algeria

Keywords
- fracture assessment
- material failure curve
- notch driving force
- API 5L
- pipeline

Abstract

The fracture assessment procedure of API 5L gas pipe steels is analysed from the viewpoint of notch fracture mechanics. The procedure is determined by the interaction between the material failure curve and the notch driving force. The material failure curves, based on three-parameter fracture criterion of (K-T-A_3) are determined by experimental tests for different laboratory specimens. The notch driving force consisted in modelling a real pipe with different geometry with a surface longitudinal notch submitted to internal pressure. The extrapolated points of the notch driving force to the material failure curve showed three critical parameters ($K_{\rho,c}$ - T_{ef} - $A_{3ef,c}$) of fracture resistance of pipe steels. These values could be applied as an important engineering parameter for structural integrity assessment of pipelines during long-term operation.

Ključne reči
- procena loma
- kriva otkaza materijala
- sila rasta zareza
- API 5L
- cevovod

Izvod

Analiziran je postupak procene loma gasovodnih čelika API 5L sa aspekta mehanike loma zareza. Postupak je određen interakcijom između krive otpornosti materijala i sile rasta zareza. Krive otpornosti materijala, zasnovane na tro-parametarskom kriterijumu (K-T-A_3), dobijaju se eksperimentalnim ispitivanjem različitih laboratorijskih epruveta. Sila rasta zareza se primenjuje u modeliranju realnog cevovoda različite geometrije sa površinskim podužnim zarezom, koja je opterećena unutrašnjim pritiskom. Ekstrapolirane tačke sile rasta zareza na krivoj otpornosti materijala su pokazale zavisnost tri kritična parametra ($K_{\rho,c}$ - T_{ef} - $A_{3ef,c}$) otpornosti na lom čelika za cevovode. Ove veličine se mogu primeniti kao bitan inženjerski parametar za procenu integriteta konstrukcije cevovoda u toku njegovog dugotrajnog rada.

INTRODUCTION

Severe damage, low fracture toughness and high pressure promote rapid fracture as opposed to delayed failure. Fracture mechanics is a tool for assessment of the nocivity of defects. Although fracture mechanics methodology has experienced tremendous advance during the last two decades, still a number of problems remains to be solved. One group of problems falls mainly under the general heading whether transferability can be relied upon. This concept of transferability of fracture mechanics results is central to the success of fracture mechanics. Transferability, results from experiments conducted on small laboratory specimens can be used to predict the fracture behaviour of a large structure for which an assessment is desired. Complicated, costly, occasionally impossible full scale tests are thus avoided. Classical fracture mechanics is based on a one-parameter estimation of the limit state of a cracked body.

Recent numerical and experimental studies have attempted to describe fracture in terms of two or three fracture parameters, /1-3/.

The ASTM E-399, /4/, testing procedure recommends certain types of specimen geometries and K_{IC} can be considered as the plane-strain fracture toughness. All specimen geometries recommended by ASTM E-399 are high constraint. Using the recommendation specimen geometry for testing creates an "ASTM Window" since their corresponding T or A_3 values are within a certain range. The A_3 quantifies the third term of Williams stress field expansion, /5/. A K_{IC} value is believed to represent a lower limiting value of fracture toughness and the ASTM E-399 may not be generally valid. Increasing the size of a specimen shifts the stress distribution closer to the K-stress. Consequently, larger specimens tend to possess better K-dominance. This may explain why a large specimen is better suited for ASTM fracture toughness K_{IC} testing in addition to the reason for the plastic zone size. This phenomenon limiting the recommendation of ASTM and can be explained using the analytical K-T and/or K-A_3 relation for common effects of specimen geometries.

This paper exploited the K-T and K-A_3 crack approach which was derived from a rigorous asymptotic solution and has been developed for a two-parameter fracture. With K as the driving force and T and A_3 as constraint parameters, this approach has been successfully used to quantify the constraints of notch-tip fields for various proposed geometry and loading configurations.

THE (K-T-A_3) APPROACH FOR CRACK

It is noted in /6/ that there is a region or volume around the crack tip where plastic deformation occurs. For highly stressed material along the crack front, this volume plays a crucial role in driving the fracture process. When plastic regions ahead of the crack front tend to stress, the stress distribution in terms of K, breaks down. The most general way to study near tip features is probably to construct a complete finite element model for the component or specimen, containing enough detail to allow the representation of near tip events. The main point, though, is to establish trends and so contribute to use low-order asymptotic expansions. Under such conditions, and in order to correlate the higher term effects to an appropriate physical parameter, some works simplified the higher terms and define the T-stress. T_{xx}, or simply the T in the direction xx is defined as constant stress acting parallel to the crack and its magnitude is proportional to the nominal stress in the vicinity of the crack.

$$K \approx \sigma_{ij}\sqrt{2\pi r}\cdot f_{ij}(\theta)+T\sqrt{2\pi r}\cdot\delta_{1i}\delta_{1j} \quad \text{as} \quad r\to\infty \qquad (1)$$

The linear elastic Williams' series solution is used for describing the crack tip stress fields. Three terms of Williams' solution, quantified by two parameters, K for the intensity of the stress field, T and A_3 for the crack tip constraint, are studied and found to be sufficient for representing the crack tip stress distribution. Ayatollahi et al., /7/ reveal that the maximum along $\sigma_{\theta\vartheta}$ is not always zero $\theta = 0$ and angular deviation can occur only for positive values of T-stress. When the T-stress is negative the maximum $\sigma_{\theta\vartheta}$ is always along in the direction of propagation, $\theta = 0$. In mode I, fracture occurs when the tangential stress $\sigma_{\theta\vartheta}$ at some point along $\theta_{\max}$ at a critical distance r_c from the crack-tip, exceeds the critical or maximum stress σ_c. The tangential stress $\sigma_{\theta\vartheta}$ near the tip is rewritten as

$$\begin{aligned}\sqrt{2\pi r}\cdot\sigma_{\theta\theta} &= K_I\cos^3(\theta/2)+T\sqrt{2\pi r}\cdot\sin^2\theta+\\ &+(3/4)A_3\sqrt{2\pi}\cdot r\big(5\cos(\theta/2)-\cos(5\theta/2)\big)\end{aligned} \qquad (2)$$

we can note $K_{app} = \sigma_{\theta\theta}\sqrt{2\pi r}$, with K_{app} representing the apparent stress intensity factor. At fracture, the critical apparent stress intensity factor $K_{app,c}$, and using Eq.(2), one then has

$$\begin{aligned}K_{app,c} &= (\sigma_{\theta\theta})_{\max}\sqrt{2\pi r_c} = K_c\cos^3(\theta_c/2)+\\ &+T_c\sqrt{2\pi r_c}\sin^2\theta_c+\\ &+(3/4)A_{3c}\sqrt{2\pi r_c}\big(5\cos(\theta_c/2)-\cos(5\theta_c/2)\big)\end{aligned} \qquad (3)$$

For mode I, assuming three terms are sufficient to characterize the crack tip stress field; we examine the case when crack does not curve, i.e. the second term in Eq.(2) or the T-stress vanishes. Eq.(3) becomes

$$K_{app} = \sigma_{\theta\theta,\theta=0}\sqrt{2\pi r} = K_I + 3\sqrt{2\pi}\cdot A_3 r \qquad (4)$$

The A_3 term in the Williams series expansion is determined by employing finite element analysis and Eq.(4) can be rewritten for high order as

$$K_{app} = \sigma_{\theta\theta,\theta=0}\sqrt{2\pi r} = K_I + B_3 r + B_5 r^2 \qquad (5)$$

where $B_3 = 3\sqrt{2\pi}\,A_3$ and $B_5 = 5\sqrt{2\pi}\,A_5$. If the stress intensity factor distribution expressed by the left side of Eq.(5) is plotted against the distance from the crack-tip r, a linear fit to the data will yield the slope m. Then, A_3 can be obtained from the slope m, that is $A_3 = m/3\sqrt{2\pi}$. For the distribution of the stress intensity factor in Eq.(1), the fit is a parabolic curve. Having both K_{app} and A_3 determined, the three term solutions in Eq.(5) give the near crack-tip stress.

MATERIAL FAILURE CURVE FOR NOTCH

A procedure of transferring (K-T) and (K-A_3) curves determined from non-standard specimens or flawed structure procedure to standard ASTM is outlined in this section. Although pipelines are manufactured from materials conforming to any number of different specifications, the focus of this section are those pipes produced under API specification 5L "specification for Line Pipe". The Material Failure Curve (MFC) has evolved into a mature technology for characterizing the fracture toughness transition.

Reviews to determine the effective T-stress and $A_{3,eff}$

To determine the Material Failure Curve, we present notch fracture mechanics (NFM) principles applied to study stress distribution at the notch tip of pipes submitted to internal pressure. Volumetric Method, presented by Pluvinage, /6/, is a meso-mechanical method belonging to this NFM, for more detail, see Ref. /8/. The Stress Difference Method (SDM) equation is used to determine the T-stress versus r distances behind the notch. It is proposed by Yang et al. /9/, using directly a single finite element (FE). This corresponds to mode I positions around the crack tip.

$$T=(\sigma_{xx}-\sigma_{yy})_{r=0,\theta=0} \quad (6)$$

The Notch Stress Intensity Factor, NSIF, is described and is defined as a function of effective distance and effective stress given by relationship

$$K_\rho=\sigma_{eff}\sqrt{2\pi X_{eff}} \quad (7)$$

The effective T-stress, T_{eff} is not singular as $r \to 0$, but it can modify to the effective crack tip plastic zone. T_{eff} can be rewritten as

$$T_{eff}=(1/X_{eff})\int_0^{X_{eff}} T_{xx}(r)\Phi(r)dr \quad (8)$$

Effective T-stress as been used as a constraint parameter. This addition to the classical plastic notch tip parameter K_ρ provides an effective two-parameter characterisation of elastic notch-tip fields in a variety of notch configurations and loading conditions. With the volumetric method, we examine the case when the crack dose not curve, i.e. the second term in Eq.(8) or the T-stress vanishes.

$$K_{eff}^c=\sigma_{\theta\theta,\theta=0}\sqrt{2\pi X_{eff}}=K_\rho+3\sqrt{2\pi}\cdot A_{3eff}\,r \quad (9)$$

The A_{3eff} term in the Williams' series expansion is determined by finite element analysis, defined by the same step in the 'Material Failure Curve ($K_{\rho,c}$, A_{3ef})' section ahead.

Material Failure Curve ($K_{\rho,c}$, T_{ef})

The relevance of the K-T crack approach, which was derived from a rigorous asymptotic solution, has been developed for a notch two-parameter fracture to determine the Material Failure Curve (MFC). With $K_{\rho c}$ as the driving force and $T_{ef,c}$ as constraint parameter, this approach has been successfully used to quantify the constraints of notch-tip fields for various proposed geometry and loading configurations.

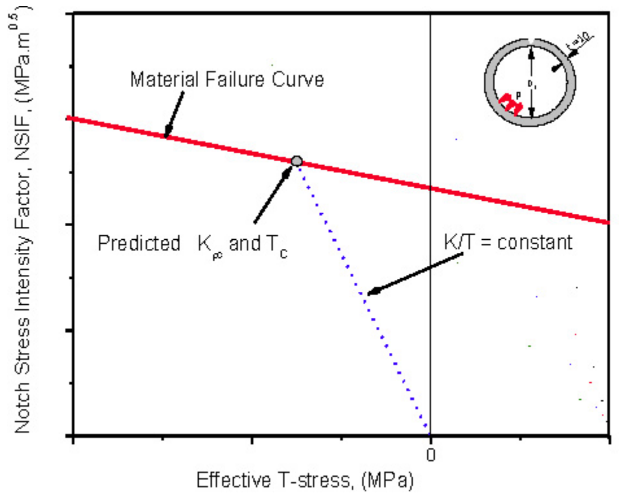

Figure 1. Prediction of the $K_{\rho,c}=f(T_{ef,c})$ curve.
Slika 1. Procena krive $K_{\rho,c}=f(T_{ef,c})$

We suggest extending the $K_{\rho c}$–$T_{ef,c}$ to different steels and with the presence of hydrogen. Different specimen geometries are presented with the notch depth of 0.5 (a/t = 0.5) after emerging in the hydrogen environment for 30 days and they compared with the results of /8/.The experimental assessment points ($K_{\rho,c}$, $T_{ef,c}$) for four specimen geometries (CT, SENT, RT and DCB) with notch aspect ratio (a/t = 0.5) are summarized in Fig. 2. These experimental assessment points allow constructing a material failure curve called also a material master curve which is approximated by the following expression

$$K_{\rho,c}=aT_{ef,c}+b \quad (10)$$

where a = –0.0843 and b = 71.6785 for the X52 pipe steel without hydrogen.

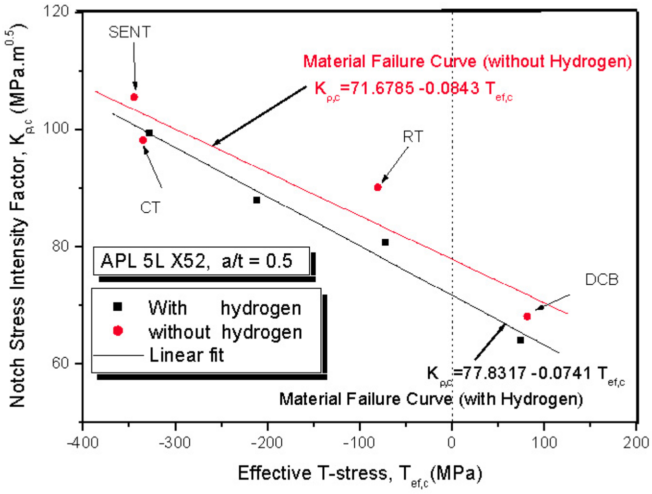

Figure 2. Experimental assessment points ($K_{\rho,c}$, $T_{ef,c}$) and material failure curve $K_{\rho,c}=f(T_{ef,c})$ for X52 pipe steel with and without hydrogen effect.
Slika 2. Tačke eksperimentalne procene ($K_{\rho,c}$, $T_{ef,c}$) i kriva otpornosti materijala $K_{\rho,c}=f(T_{ef,c})$ za čelik cevovoda X52 sa i bez uticaja vodonika

The degradation of the notch stress intensity factor with the presence of constraint is in the range 5.8–9.8% for different specimens. The shift between the virgin SENT specimen and the hydrogenated is small, however a substantial difference is noted in the DCB specimen (about 10%). This deviation is ascribed to the exploit of specimens between tension and flexion loading. The decreasing of the notch stress intensity factor values for different specimens can be explained by the degree of constraint. Increasing the yield stress increases the constraint parameter.

Material Failure Curve ($K_{\rho,c}$, $A_{3,ef}$)

For any flawed specimen or structure, a notch driving force may be established by running a linear elastic FEA for the geometry and any applied load to determine the pair ($K_{\rho,c}$, $A_{3,ef}$). For a surface notch, the crack front is a curved line. A ($K_{\rho,c}$, $A_{3,ef}$) pair and a notch driving force at each point along the notch front are present as the far field load is increased. By putting entire notch driving forces along the notch front together, the notch driving force for the surface notch becomes a curved front as depicted in Fig. 3a.

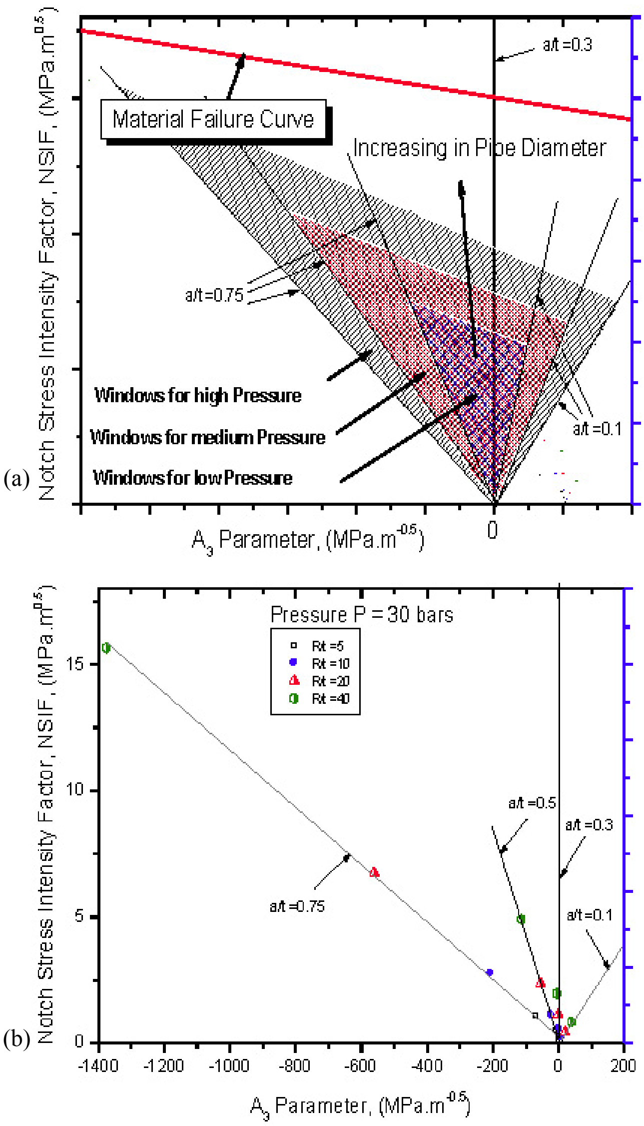

Figure 3. Example of Master curve in ($K_{\rho,c}$, $A_{3,ef}$) plane for different pressure and diameters.
Slika 3. Primer „master“ krive u ravni ($K_{\rho,c}$, $A_{3,ef}$) za različite pritiske i prečnike

Since ($K_{\rho,c}$, $A_{3,ef}$) varies from point to point along the notch front for a given far field load. Each point on the curve represents the condition of the opening stress at a particular point in the notch front of the surface crack. For instance, the left point of the curve may represent the condition of the opening stress at the deepest point of the surface notch and the right point corresponding to the point where the crack front intersects with the surface (Fig. 3b). For common specimen geometries, the relation between $K_{\rho,c}$ and $A_{3,ef}$ is tabulated from numerical calculations for convenience. Since the ratio between $K_{\rho,c}$ and $A_{3,ef}$ is a constant for a given geometry. In Fig. 3b, the point (0,0) represents the condition of no applied load. The two points (0,0) and ($K_{\rho,c}$–$A_{3,ef}$) from the driving force are represented in a straight line in the ($K_{\rho,c}$–$A_{3,ef}$) plane and the intersection of the notch driving force with the material failure line yields, determined in /8/, has predicted the particular flawed structure.

Combination of MFC ($K_{\rho,c}$, T_{ef}, $A_{3,ef}$)

Recently, some publications have carried out a complete analysis of higher order crack fields in power-law hardening materials and have shown that a two-term expansion is not sufficient to describe the near tip fields while more than three terms are redundant.

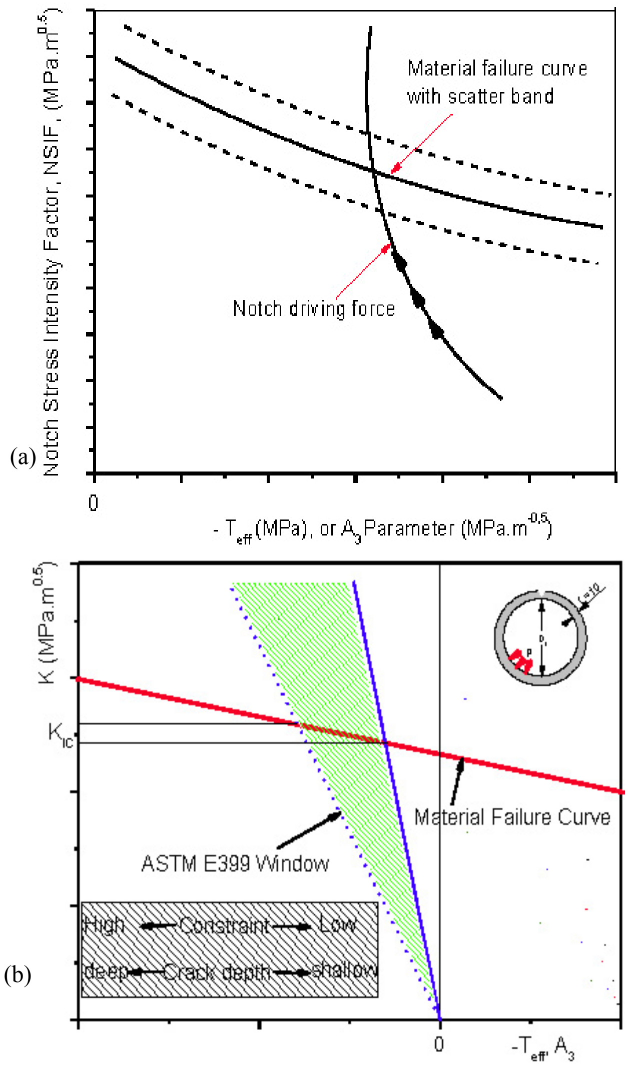

Figure 4. Material Failure Curve points ($K_{\rho,c}$, $T_{ef,c} - A_{3,ef}$) and the driving force for X52 pipe steel.
Slika 4. Tačke krive otpornosti materijala ($K_{\rho,c}$, $T_{ef,c} - A_{3,ef}$) i sila rasta za čelik X52 cevovoda

Note that the criterion of ($K_{\rho,c}$, T_{ef}, $A_{3,ef}$) fracture at any point on the notch reaches the critical values of the material. The driving forces reaches the intrinsic curve of rupture with increasing load. The test ASTM E399 method recommends certain types of specimen geometries with crack length $a \geq 2.5(K_{IC}/\sigma_e)^2$, so that K_{IC} can be conceived as the fracture toughness in plane deformation of pipe. This situation is not realistic, since most pipelines have a thickness not exceeding 25 mm. All geometries of specimens recommended by the ASTM, containments have very high constraint. The shaded area represents the window of the ASTM test if recommended having depths of $a/t = 0.45$ to 0.55.

CONCLUSION

We have adopted the two non-vanishing terms from the series solutions of Williams'. The effects of the two terms on the stress level are studied for extreme cases such as very shallow or very deep notches. We found that the further terms may not be negligible for notch length.

A mesofracture approach of the fracture toughness transferability problem is proposed. The crack (K-T-A_3) methodology has been modified to create the ($K_\rho - T_{ef} - A_{3,ef}$) three parameters fracture resistance criterion. A parabolic relationship is found between these three parameters and allows building a fracture toughness window including data from a large range of pressure and geometry.

Procedures to shift the mechanical properties curve between pipelines of different in-plane constraint levels are developed which enable the determination of the transition curve of non-standard flawed structures from experimental results of standard specimens.

REFERENCES

1. Hadj Meliani, M., Azari, Z., Pluvinage, G., *Constraint Parameter for a Longitudinal Surface Notch in a Pipe Submitted to Internal Pressure*, Key Engineering Materials, Advances in Strength of Materials, Vol. 399 (2009), pp.3-11.
2. Hadj Meliani, M., Matvienko, Y.G., Pluvinage, G., *Two-parameter fracture criterion ($K_{\rho,c}$-$T_{ef,c}$) based on notch fracture mechanics*, Intern. J of Fracture, Vol.167, No.2, 2011, pp.173-182.
3. Chao, Y.J., Liu, S., Broviak, B.J., *Brittle fracture: variation of fracture toughness with constraint and crack curving under mode I conditions*, Experimental Mechanics 41(3), 2001, pp.232-241.
4. Norm. ASTM E813-89, Standard Test Method for J_{Ic}, A measure of fracture toughness, April 1991.
5. Williams, M.L., *On the stress distribution at the base of stationary crack*, ASME J Appl Mech 1957; 24 : 109-14.
6. Pluvinage, G., Fracture and Fatigue Emanating from Stress Concentrators, Kluwer, Publisher, 2003.
7. Ayatollah, M.R., Pavier, M.J., Smith, D.J., *Determination of T-stress from finite element analysis for mode I and mixed mode I/II loading*, Int. J of Fracture 91, (1998), pp.283-298.
8. Hadj Meliani, M., Azari, Z., Pluvinage, G., Matvienko, Y.G., *Variation of material failure curve with constraint*, Procedia Engineering, Volume 10, 2011, pp.710-715.
9. Yang, B., Ravi-Chandar, K., *Evaluation of elastic T-stress by the stress difference method*, Engng. Fract. Mech. (1999) 64:589-605.