International Journal of Engineering Science 121 (2017) 182–193

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Redirection of a crack driven by viscous fluid

Monika Perkowska[a], Andrea Piccolroaz[b], Michal Wrobel[c], Gennady Mishuris[d,*]

[a] EnginSoft S.p.A., Via della Stazione 27, frazione Mattarello, 38123 Trento, Italy
[b] Dipartimento di Ingegneria Civile, Ambientale e Meccanica, Universita di Trento, via Mesiano, 77 I-38123 Trento, Italy
[c] Faculty of Energy and Fuels, AGH-University of Science and Technology, 30 Mickiewicza Avenue, 30–059 Krakow, Poland
[d] Department of Mathematics, Aberystwyth University, Ceredigion SY23 3BZ, Wales, United Kingdom

ARTICLE INFO

Article history:
Received 6 September 2017
Revised 22 September 2017
Accepted 25 September 2017
Available online 13 October 2017

Keywords:
Direction of the fracture propagation
Hydraulic fracture
Toughness dominated regime
Viscosity dominated regime

ABSTRACT

As shown by Wrobel, Mishuris, and Piccolroaz (2017), the hydraulically induced tangential traction on fracture walls changes local displacement and stress fields. This resulted in the formulation of a new hydraulic fracture (HF) propagation condition based on the critical value of the energy release rate that accounts for the hydraulically-induced shear stress. Therefore it is clear that the crack direction criteria, which depend on the tip distributions of the stress and strain fields, need to be changed. We analyse the two commonly used criteria, one based on the maximum circumferential stress (MCS) and another - on the minimum strain energy density (MSED). We show that the impact of the hydraulically induced shear stress on the direction of the crack propagation is negligible in the case of large material resistance to fracture, while for small toughness the effect is significant. Moreover, values of the redirection angles, corresponding to the so-called viscosity dominated regime ($K_{IC} \to 0$), depend dramatically on the ratios of the stress intensity factors.

© 2017 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license.
(http://creativecommons.org/licenses/by-nc-nd/4.0/)

1. Introduction

In the standard approach of Linear Elastic Fracture Mechanics (LEFM), the onset of crack propagation is found by using the energy release rate (ERR) criterion which, in the case of an isotropic elastic material, assumes the form (Rice, 1968):

$$\mathcal{E} = \frac{1+\nu}{E}\left[(1-\nu)\left(K_I^2 + K_{II}^2\right) + K_{III}^2\right] = \mathcal{E}_C \equiv \frac{1-\nu^2}{E}K_{IC}^2, \tag{1}$$

where ν is the Poisson's ratio and E is the Young's modulus, while $\mathcal{E}_C$ and K_{IC} are the experimentally found critical values of ERR and material toughness, respectively. Here K_I, K_{II} and K_{III} are the stress intensity factors pertaining to three basic modes of fracture load. For pure Mode I loading, Eq. (1) transforms into the well known Irwin criterion for crack propagation (Irwin, 1957):

$$K_I = K_{IC}. \tag{2}$$

However, for the mixed mode loading, determination of the direction of the crack growth is of crucial importance.

* Corresponding author.
E-mail address: ggm@aber.ac.uk (G. Mishuris).

https://doi.org/10.1016/j.ijengsci.2017.09.009
0020-7225/© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license. (http://creativecommons.org/licenses/by-nc-nd/4.0/)

The path of possible crack kinks has been extensively studied for many years (see Cotterell & Rice, 1980; Leblond, 1989). Most of the developed theories are based on the information from the Irwin-Williams expansion of the crack tip field (Williams, 1957). Some more advanced criteria utilise additional material parameters related to the underlying physics or other arguments (size of the process zone, size of the possible kink, and so on).

The collection of criteria for kink initiation developed so far to determine the redirection angle in fracture mechanics is extensive. Beginning with the most popular examples: maximum circumferential stress (MCS) (Erdogan & Sih, 1963) and minimum strain energy density (MSED) (Liebowitz & Sih, 1968; Sih, 1974), we can list the maximum strain energy release rate (MSERR) criterion (Hussain, Pu, & Underwood, 1974; Palaniswamy & Knauss, 1972), the local symmetry criterion (Goldstein & Salganik, 1974), the maximum dilatational strain energy density (MDSED) criterion (Theocaris & Andrianopoulos, 1982; Yehia, 1991), the maximum determinant of the stress tensor criterion (Papadopoulos, 1988), the J-criterion (Hellen & Blackburn, 1975), the vector crack tip displacement criterion (Li, 1989), the maximum normal strain criterion (Chang, 1981), the maximum potential energy release rate criterion (Chang, Xu, & Mutoh, 2006), the so-called T-stresses criteria (Williams & Ewing, 1984), and many others. Clearly, the applicability of any specific approach should be justified on a case by case basis, using the strength properties of the materials involved in the study, the loading conditions and available experimental data to validate the selection of criterion. It follows that there is no universal criterion valid for all possible applications. However, in many situations the discrepancies in prediction given by the different criteria are not large and are usually observable only in the deviation from the pure Mode I load (especially for the infinitesimal kinks most of the criteria coincide - see Cotterell & Rice (1980)).

When considering hydraulic fracture (HF), the prediction of the possible crack propagation path becomes even more challenging, as the interaction between the pressurised fluid and the solid and complicated fracture network substantially increases the complexity of the problem (Paluszny & Zimmerman, 2017; Salimzadeh, Paluszny, & Zimmerman, 2017). Moreover, the sets of credible data that could be used to verify theoretical models are limited or inaccessible. There have also been arguments that cast doubt on the applicability of some of the fracture criteria when applied to brittle fracture (Chudnovsky & Gorelik, 1996) and hydraulic fracture (Cherny et al., 2017)).

Wrobel, Mishuris, and Piccolroaz (2017) introduced a modified formulation of the HF problem, accounting for a hydraulically induced tangential (asymmetrical) traction at the crack faces. It was shown that, due to the order of the tip singularity of the hydraulic shear stress, this component of the load cannot be omitted when computing ERR. A new parameter, the hydraulic shear stress intensity factor (K_f), was introduced and proved to play an important role in the HF process. The amended crack propagation criterion, under remote Mode I loading conditions, was formulated as:

$$\mathcal{E} = \frac{1-\nu^2}{E}\left[K_I^2 + 4(1-\nu)K_I K_f\right] = \mathcal{E}_C. \tag{3}$$

This formula includes both, the standard stress intensity factor for Mode I, K_I, and the newly introduced hydraulic shear stress intensity factor, K_f.

Here we analyse how the shear stress induced by moving fluid at the crack faces influences the crack propagation direction in the most general case, when all fracture modes (Mode I, II, III) are taken into account. We focus on two commonly used criteria, Maximum Circumferential Stress (MCS) and Minimum Strain Energy Density (MSED). Presently, we could not find any experimental data to verify the results and therefore determine which of the two criteria is more relevant to hydraulic fracture problems.

The structure of this paper is as follows. In Section 2 a methodology for the computation of the ERR in presence of the hydraulically induced shear stress for mixed mode loading is presented. An asymptotic representation of the stress and strain fields in the vicinity of the fracture tip is given. In Section 3, in a new setting, two criteria are chosen for use in determining the crack propagation angle in the presence of hydraulic tangential traction. Corresponding results are analysed with respect to various crack propagation regimes and values of the Poisson's ratio, and are compared with one another. Finally, we summarise our conclusions in Section 4.

2. Computation of the energy release rate accounting for the shear stress induced by fluid in a mixed mode setting

In the framework of the LEFM, the ERR is computed using the standard J-integral argument (Huber, Nickel, & Kuhn, 1993; Rice, 1968; Richard, Fulland, & Sander, 2004):

$$\mathcal{E}(z) = \lim_{\delta\to 0} J_x^\delta(z) = \lim_{\delta\to 0}\int_{\Gamma_\delta}\left\{\frac{1}{2}(\boldsymbol{\sigma}\cdot\boldsymbol{\varepsilon})n_x - \boldsymbol{t}_n\cdot\frac{\partial \boldsymbol{u}}{\partial x}\right\}ds, \tag{4}$$

where Γ_δ is a circular contour of radius δ around the fracture tip, contained in a plane orthogonal to the crack front, $\mathbf{n}$ is the outward normal to the contour Γ_δ, and $\mathbf{t}_n = \boldsymbol{\sigma}\mathbf{n}$ is the traction vector along Γ_δ (see Fig. 1).

The classical fracture criterion (1) is derived directly from formula (4), for an arbitrary mixed mode deformation and smooth crack front. It has been widely adopted in the analysis of hydraulic fracture (Adachi, Siebrits, Peirce, & Desroches, 2007; Bunger, Detournay, & Garagash, 2005; Garagash, 2006; Garagash & Detournay, 1999; Perkowska, Wrobel, & Mishuris, 2016; Wrobel & Mishuris, 2015) on the ad hoc assumption that the hydraulically induced tangential traction is small compared to the net fluid pressure and can thus be neglected. However, Wrobel et al. (2017) showed that the singularity of the hydraulic shear stress is stronger than that of the fluid pressure, and therefore the former cannot be omitted when

Download English Version:

https://daneshyari.com/en/article/5022629

Download Persian Version:

https://daneshyari.com/article/5022629

Daneshyari.com