Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

An Energetic Approach to Simulate 2D Ductile Crack Growth

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ABSTRACT

This article presents an energetic approach which aims at estimating dissipated energy in the fracture process during ductile tearing represented by an intrinsic parameter G_{fr}. A fracture criterion, which accounts for the crack extension length, is defined and lies on a critical energy dissipation rate, noted G_c. From a simple energetic balance, it is shown that G_c could be related to the J plastic part. A new formulation of the fracture criterion is then proposed, based on the comparison between G_{fr} and a variation of J plastic part. In particular, it allows to model non uniform propagation by defining a local criterion. This approach is used to model 2D crack growth in a cracked ring, loaded in compression. It is shown that triaxiality effect, such as tunnel effect, could be successfully represented with this approach.

INTRODUCTION

In recent years it has become of growing interest to study the ductile behaviour of cracked components. So far, a number of methods have been proposed to obtain critical parameters able to describe crack initiation and subsequent growth (J-Δa Curves). However, there is now experimental evidence that these parameters depend upon specimen geometry and loading conditions [1].

The models proposed by Rice and Tracey [2], Gurson [3] or Rousselier [4] for instance, have overcome some of these difficulties. The approach refers to the local approach and is an attempt to account for the micro-mechanical behaviour of the material. For ductile tearing, it consist in initiation, growth and coalescence of cavities which are present in the material matrix. However, two major limitations of these models are the numerical costs associated with the simulations, particularly for 3D structures, and the identification of the parameters, which are still the subject of important investigations.

Nevertheless, engineers still need simple and fast method for structural integrity analysis. This is the motivation to develop a new approach, called G_{fr} approach. This energetic approach uses only two independent parameters J_i and G_{fr} to describe respectively crack initiation and propagation. The first one, noted J_i, is related to the crack tip blunting phenomena. Such an initiation criterion has been shown to be intrinsic to the material [5]. The second parameter represents the dissipated energy in the fracture process for a unitary extension of crack area. In some cases, it could be numerically estimated by the representing crack growth process in two phases : crack extension at constant imposed load line displacement followed by damage accumulation near the crack tip at constant crack length. The crack extension is performed by a simultaneous release of several nodes, in order to allow the calculation of the Rice integral with integration path radius smaller than the distance of the two consecutive crack tips [6]. If the crack extension length is large enough, it is possible to define a path independent parameter, noted G_{local}, even in large scale yielding conditions. The following assumptions allow to define a fracture criterion based on this G_{local} parameter :

- For ductile tearing, the damage mechanism is related to plastic deformations around the crack tip : only the plastic part of G_{local} will be accounted in the criterion.
- As mentioned above, the crack growth will be simulated with a discontinuous representation, with a fixed crack extension length λ. The dissipated energy for this extension is supposed to be proportional to the length λ.
- Fracture energy is supposed to be intrinsic to the material and constant during crack growth. A dissipation rate G_{fr} is then defined and corresponds to the fracture energy of a unit of a crack area extension.

The crack extension is then performed when the plastic part of G_{local} reaches a critical value, G_c, given by :

$$G_c = \overline{\lambda}.G_{fr} \qquad (1)$$

where $\overline{\lambda}$ is the dimensionless measure of λ. Several studies have validated this criterion and its independence to the crack extension length λ choice and the transferability of G_{fr} parameter [6,7] from laboratory specimens to structures.

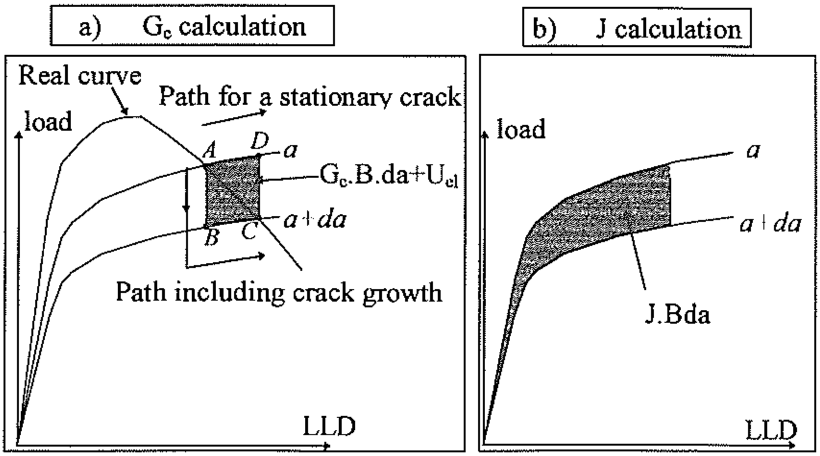

Figure 1 : geometric interpretation of the criterion.

THE NEW FORMULATION OF THE FRACTURE CRITERION

One of the main features of this criterion is its relation with the J integral. Indeed, several results [7,8] lead to the following interpretation :

- assuming that the crack growth process is represented by an increasing damage at constant crack length followed by crack extension associated to a critical damage at constant load line displacement, the behaviour of the specimen can be simply illustrated in Figure 1-a where the load drops from point A to point B, then from point B to point C.
- If crack growth was not accounted for, point D would represent the state of the structure at the same load-line displacement value than point C.

Therefore, the energy dissipated during crack growth is simply given by the plastic part of area ABCD. In [7], This area is found to be equal to $G_c.B.\lambda$, where B is the specimen thickness.

It is also worth noting that this definition of G_c for the propagation is nearly similar to the J integral : By definition, for non linear elasticity the J integral represents the energy released rate corresponding to an infinitesimal crack advance, i.e.:

$$J = -\frac{d\Pi}{B.da} \tag{2}$$

where Π is the total potential energy and a the length of the crack. Figure 1-b schematises this principle, where J is given by the difference of the areas between two curves corresponding to two different crack lengths (a and a+da). It appears on this figure that G_c could be estimated from the J variations, calculated in the configuration corresponding to the crack length a, between points A and D. In the same manner, the plastic component of this energy can be obtained from the J plastic part variation, between these same points. This interpretation offers therefore a new method to estimate the parameter G_c : it is no longer based on the estimation of a local energy release rate, but from J integral calculations in stationary configurations. Thus, for the crack extension λ between points A and D on Figure 1-a, the following relationship is proposed :

$$G_c = \bar{\lambda}.G_{fr} = J_{pl}(D) - J_{pl}(A) \tag{3}$$

where J_{pl} refers to J plastic part. This relationship allows to model ductile tearing propagation only from stationary calculations : the crack initiation consists always in searching the load corresponding to a J value which verifies the criterion J_i. Then a stationary calculation in the configuration corresponding to the initial crack length a is performed, to determine the J plastic part evolution versus the imposed load up to the imposed displacement for a crack length (a+λ) (point D in Figure 1-a). The load corresponding to this imposed displacement on the real curve is obtained from the stationary calculation of the geometry with the crack length (a+λ) (point C on Figure 1-a). In fact, the relationship (3) offers two possibilities of calculation :

- *The length of the crack increment λ is fixed*: The point D, whose value $J_{pl}(D)$ verifies the criterion, is found in the configuration before the crack extension (crack length a). The load value on the real curve (corresponding to point C on Figure 1-a) is then obtained from stationary calculation in the configuration after the crack growth (crack length a+λ), and corresponds to the same imposed displacement as point D.

- *Imposed displacement increments on the structure are fixed*: In this case, displacements corresponding to points A and D are known and the crack extension length becomes the unknown parameter. The variation of J_{pl} between these two points is calculated in the configuration before crack growth (crack length a) and allows to deduce the length of the associated crack extension, by inverting relation (3) :

$$\bar{\lambda} = \frac{J_{pl}(D) - J_{pl}(A)}{G_{fr}} \tag{4}$$

This type of calculation can be achieved because of the independence of the criterion to the crack increment length. For real crack, it is possible to calculate locally along the crack front J values and their plastic component. Similarly to the J_i approach [5], a local criterion based on the G_{fr} concept can be proposed to estimate a local propagation, and then to model phenomena related to the stress triaxiality, such as tunnel effect. Moreover, it is no longer necessary to mesh the total propagation zone, since the new method of calculation lies on stationary calculations. The evolution of the defect as a function of the imposed load can be obtained.

This method implies that the global state of the structure, i.e. load, displacement and crack length a, on point C of the real curve (see Figure 1-a) is approached by the state of this point on the load-displacement curve with a stationary crack, with a length equal to a. This assumption is often used in simplified method using J. This is confirmed by a number of investigations and particularly those of Joyce et al [9] and Sharobeam et al [10]. Joyce et al [9] have compared load-displacement curves obtained from CT specimens, with machined notches or fatigue cracks. The first type of specimen remains stationary whereas the other presents large crack growth. A good agreement is obtained for two specimens with identical crack sizes, the first specimen with a machined notch and the second one with a fatigue crack. Sharobeam et al [10] observed the same behavior and explain it with the load separation principle, which implies that the load F can be represented as a multiplication of two separate and independent scale functions :

$$F = g\left(\frac{b}{W}\right).h\left(\frac{v_{pl}}{W}\right) \tag{5}$$

where g is a crack geometry function that depends on the remaining ligament b and h is a material deformation function of the plastic displacement v_{pl}. They show that this load separation is valid when the crack grows. The functions g and h obtained, in this case, are equal to the functions of the stationary case.

APPLICATION TO A CRACKED RING IN COMPRESSION

To illustrate the possibility of the approach for complex crack growth, the case of a cracked ring loaded in compression is studied. The detail of this application could be found in reference [7].

Test presentation

The considered material, a Tu52B ferritic steel, presents a Young modulus of 213 GPa, a yield stress σ_y of 345 MPa and an ultimate stress σ_u of 563 MPa. The chemical composition of the material is as follows (%wt) :0.19C, 0.39Si, 1.33Mn, 0.014P, 0.022S. The value of J_i is determined on the J-Δa curve from observation with an electronic microscope of a CT specimen stretched zone [5] (B=25 mm, W= 50 mm). The obtained value for J_i is approximately 100 kJ/m^2. G_{fr} is determined numerically with this CT specimen following the method proposed in [7]. A value of 84 kJ/m² is found.

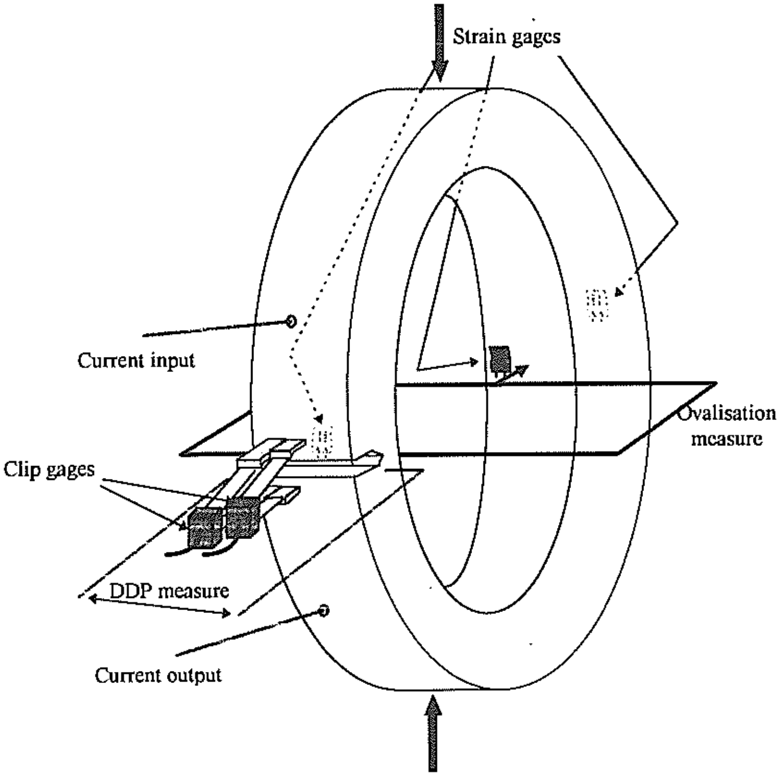

Figure 2 : presentation of the cracked ring

The considered test (figure 2) consists in applying a monotonous compressive load on a ring containing an external notch. The outer and inner diameters of the ring are respectively 216 and 150 mm. Its thickness equals to 35 mm and the depth of the machined notch is 8 mm. The ring is first fatigue precracked until an average crack length of 10.75 mm is obtained. During the test, stable propagation stages are followed by unstable phases. These different phases are clearly distinct on the thermally marked crack face. The crack extension for the first stable tearing phase is approximately 8.2 mm. Measured parameters during the test are : the load, the imposed jack displacement, the ovalisation in the crack plan and the CMOD.

F.E. analysis

For finite elements analysis, performed with the CEA software CASTEM 2000, considering symmetries, only a quarter of ring is meshed. Figure 3 presents the initial mesh with the real fatigue crack front modelled. In this calculation with crack propagation, values of the jack displacement increment are fixed. Crack extension between two of these displacements is then determined from the relationship (4). The crack is always assumed to grow in the same direction whereas the calculated crack extension has theoretically to be normal to the front. However, except for some isolated points, the global propagation direction and the normal along of the front are similar. But the estimation of the crack extension may be more approximated near the edge of the ring because of an important tunnel effect. The calculation is performed with a large displacements assumption to account for important geometric modifications. The simulation is realised up to the first instability (which corresponds to an average ductile tearing crack extension of about 8.2 mm). Six stationary calculations are performed to model the stable ductile tearing crack growth.

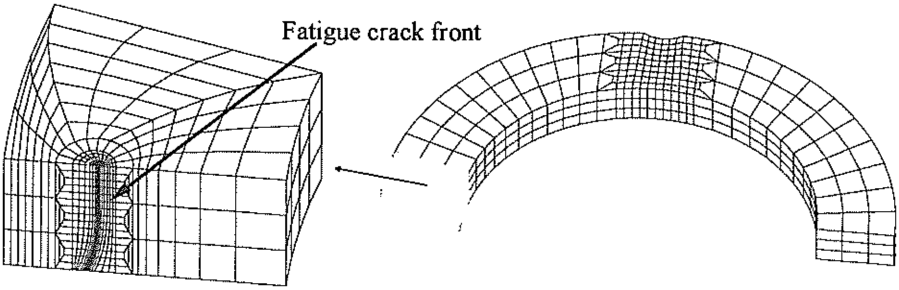

Figure 3 : 3D mesh of the fatigue crack front.

In Figures 4 and 5, the numerical results are compared to the experimental data. One observes the good agreement between the test and the calculation, especially for the ovalisation and the crack propagation, so for the average value along the crack front than for the maximal one. The predicted final crack front is compared to experimental one in Figure 6, with a good agreement.

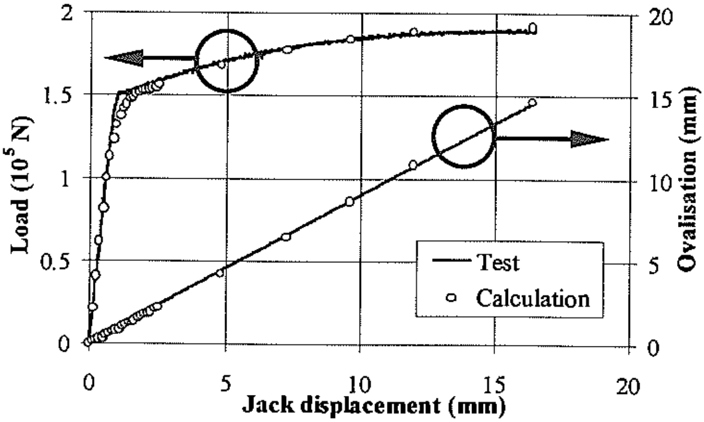

Figure 4 : load and ovalisation versus jack displacement.

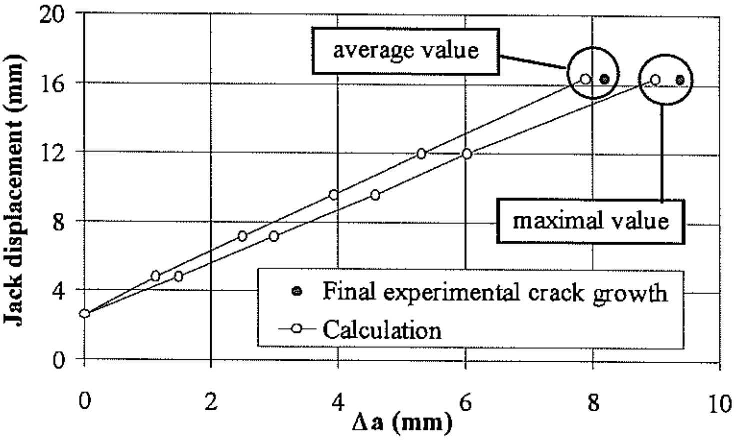

Figure 5 : Experimental and predicted crack growth.

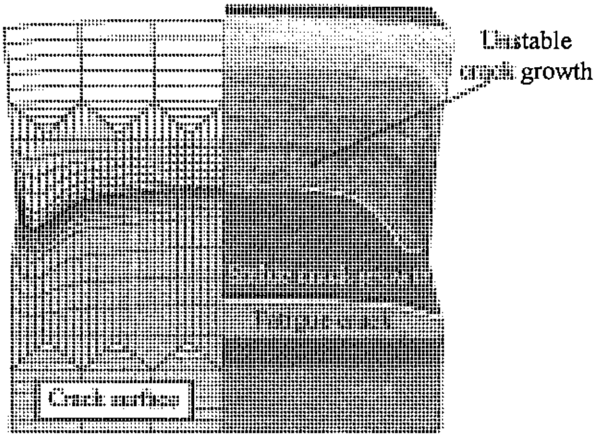

Figure 6 : Prediction of the local crack extension and comparison with the experimental final crack.

It appears therefore that the method based on the variation of the plastic component of J integral allows to model correctly the crack propagation, in particular by taking into account phenomena linked to the influence of the stress triaxiality such as the tunnel effect.

CONCLUSION

The principle of a recent energetic approach to model ductile tearing has been recalled. It is based on two parameters that are shown to be intrinsic to the material, J_i and G_{fr}, are proposed to describe crack initiation and propagation, respectively. A global energetic balance allows to propose a geometric interpretation of the criterion, comparable to the J integral one.

It is then shown that the calculated critical dissipation rate G_c, required for a crack extension of λ, can be related to the J plastic part variation. It allows the simulation of the crack growth process only from stationary F.E. calculations, even for real defects propagation.

This approach has been applied to a cracked ring, subjected to compression. It is shown that the global behaviour, i.e. load and ovalisation versus load line displacement, is correctly simulated. The predicted propagation is also found to be in a good agreement with the experiment, and reproduces well the observed tunnel effect. G_{fr} and J_i, obtained from test on CT specimens, are local energetic parameters and are therefore able to take into account triaxiality effects.

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