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Damage monitoring in fracture mechanics by evaluation of the heat dissipated in the cyclic plastic zone ahead of the crack tip with thermal measurements

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ABSTRACT

Dissipated energy ahead of the crack tip represents a useful tool to study the fatigue crack growth. In this regard, different analytical and numerical models were proposed in literature to investigate the role of dissipated energy in fracture mechanics and experimental techniques were used to validate them. The experimental measurement of dissipated energy requires an accurate equipment and suitable techniques that may restrict the applications only to laboratory tests.

In this work, an experimental approach by using the thermographic technique has been used to assess the heat dissipated at the crack tip in the cyclic plastic zone. The proposed approach is based on the evaluation of the heat source that occurs at the twice of the loading frequency directly related to the plastic phenomena around the crack tip. This index showed to be more suitable for on field measurement. By monitoring the fatigue crack growth during a fracture mechanics test carried out on the martensitic steel AISI 422, a similar Paris Law model was obtained between the crack growth and the heat dissipated per cycle. Moreover, it was obtained a fourth power dependence of heat dissipated energy and Stress Intensity Factor (SIF) in agreement with numerical and analytical models present in literature.

1. Introduction

Material fatigue behaviour in presence of crack depends on several factors related to the material and it is governed by different micro-mechanisms of damage at the crack tip. The first approach for describing the crack growth behaviour was proposed by Paris and Erdogan [1]. In their work the crack growth rate is expressed as a function of the stress intensity factor (SIF), [2]. In this regard, the constants of Paris's Law can be obtained by use of conventional methods according to Standards [3], by means of experimental and non-destructive techniques [4–18].

In the last years, many works [19–23] have focused their attention to the energy dissipated at the crack tip and to a possible relation with the growth of cracks. The energy based approach, proposed firstly by Weertman [19], links the crack growth rate with the critical energy to create a unit surface area. Moreover, this approach predicts a fourth power dependence of the crack growth rate and Stress Intensity Factor (SIF). Similar results were obtained by Klingbeil [20], where the crack growth in ductile solids is governed by the total cyclic plastic dissipation ahead of the crack. In [21] Mazari

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et al. starting from the Weertman's and Klingbeil's approach, developed a new model in which a similar Paris Law model was obtained between the crack growth and the heat dissipated per cycle.

The Dimensional Analysis approach was used in [22] to describe the fatigue crack growth rate as function of an energy parameter through a similar Paris-like model.

The experimental approaches used in literature aimed to determine the critical energy (U_c) were based on the use of strain gages in the plastic zone [23,24], calorimetric measurements [25], and hysteresis loop evaluation [21]. However, these approaches require an off-line measurement and processing of data with consequent high testing time and cannot be applied on actual structural components.

Infrared Thermography (IRT) is a full-field contactless technique used in many fields such as, non-destructive testing (NDT), process monitoring and evaluation of heat sources during fatigue tests. This technique was already proposed for the study of the fracture behaviour of materials subjected to fatigue loading [11–18]. In particular, a temperature rise due to the heat dissipations can be observed around the crack tip where the plastic zone is located. In this regard, Carrascal et al. [8] used IRT for evaluating the Paris Law constants of a polymer (polyamide) with an experimental methodology. A good agreement was found with respect to traditional calculation methods. Cui et al. [9], applied IRT to study the fatigue crack growth of magnesium alloy joints and demonstrated the potential of IRT in predicting the threshold value for unstable crack growth.

In the work of Meneghetti et al. [26], experimental tests were performed for evaluating the specific heat energy per cycle averaged in a small volume surrounding the crack tip from temperature measurements.

The above exposed procedures may find limitation in those cases in which temperature changes on material related to the plastic zone are very low (short cracks) and, moreover, high performance equipment and a difficult set-up are required. This is the case, for instance, with brittle materials (such as martensitic steels), welded joints and aluminum alloys [27–29].

Interesting results in assessment of plastic zone and SIF were obtained by using the Thermoelastic Stress Analysis (TSA) [30–37]. By knowing the sum of the principal stresses, it is possible to determine the stress intensity factor and, at the same time, it is possible to determine the crack growth rate by analyzing the phase data. In this regard, Ancona et al. [38] proposed an automatic procedure based on TSA, to assess the Paris Law constants and to study the fracture behaviour of 4 stainless steels.

The aim of the work is to put the basis for a residual life estimation of a component in service conditions with a full field, contactless experimental technique able to determine the crack tip position and assess the dissipated energy per cycle. In this work, in particular, it will be presented the algorithm able to estimate the dissipated energy and define the crack tip position. Paris curve form thermographic data will allow a residual life estimation once the material is characterized.

Three CT steel (AISI 422) specimens were used and tested according to ASTM E 647-00 and the monitoring of crack tip growth was performed in a continuous manner by means of a cooled IR camera. Thermal data were processed in the frequency domain in order to extract the heat source related to the heat dissipated at the crack tip. Then, a simple method was used for estimating the heat energy dissipated per cycle. A similar Paris Law model was obtained between the crack growth and the heat dissipated per cycle. Moreover, it was obtained a fourth power dependence of heat dissipated energy and Stress Intensity Factor (SIF) in agreement with numerical and analytical models present in literature.

The proposed approach seems very promising for the on-line monitoring of crack growth during testing through a set-up which is simple compared to other techniques. Moreover, a simple specimen preparation is required, which makes the proposed procedure also suitable for the monitoring of actual structural components.

2. Theory

The heat dissipated per cycle surrounding the crack tip was evaluated taking into account a theoretical model proposed in [39]. It can be noticed in Fig. 1, that a control volume V contains the plastic area A_p of radius r_p around the crack tip. In order to deal with a detailed analysis of all the effects affecting the material behaviour, it is possible to write the first law of thermodynamics, in the well-known form to describe such phenomena:

$$W_p = \Delta U + Q \tag{1}$$

where W_p represents the mechanical energy per cycle, ΔU is the internal energy due to microstructural rearrangements, to the formation of persistent slip bands and to all the phenomena related to irreversible dislocation movements. A portion of this energy does not remain under the mechanical form but switches into heating, in particular, it contributes to the irreversible heat sources development in the material and then, affects the temperature growth [40]. Q represents the heat exchanged by convection, conduction and radiation that in a steady-state condition will correspond at the heat generated per cycle by the body during the fatigue test. All quantities are expressed in unit of volume of material.

To highlight the different energy contributions affecting the material undergoing fatigue loading (with particular regard to the energy rising in the material), the Eq. (1) can be split in several terms:

$$W_p = \oint \sigma_{ij} d\varepsilon_{ij} = \Delta U + Q = Q + E_p + E_d \tag{2}$$