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Automatic procedure for evaluating the Paris Law of martensitic and austenitic stainless steels by means of thermal methods

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ABSTRACT

Determination of the Paris Law constants implies the knowledge of both Stress Intensity Factor (SIF) and the crack growth rate (*da*/*dN*). In this regard, the crack length and the SIF values can be measured using various methods suggested by literature and proposed by Standards, but most of them require an off-line measurement of the crack with consequent high testing time and cannot be applied on actual structural components.

In this work, the Thermoelastic Stress Analysis (TSA) technique is used for the monitoring of fatigue crack growth during fracture mechanics tests on four stainless steels: AISI 422 and ASTM A182 grade F6NM with martensitic lattice and CF3M and CF8M with austenitic lattice. In particular, an automatic procedure based on the TSA technique was proposed for the continuous evaluation of the crack tip position and the SIF value. Advantages with respect to classical methods can be obtained in terms of reduction of: testing time, experimental set-up, data processing and data report.

1. Introduction

Paris's Law describes the behaviour of cracked materials subjected to dynamic loading and it implies the knowledge of both the stress intensity factor (SIF) and the crack growth rate (*da/dN*) [1,2]. In this regard, these parameters can be obtained by use of conventional methods according to Standards [3], by means of experimental and non-destructive techniques [4–21]. In particular, the most widely diffused methods used for the monitoring and the measurement of crack growth rate are microscopy, extensometry, ultrasound, X-ray and DIC (Digital Image Correlation) [3,4–10].

Saka et al. [5] proposed a non-destructive method for evaluating a 3D surface crack based on a magnetic field induced in the air by DC current flow in materials. This method requires two probes for application of the DC current and cracks have to be extremely small in comparison with the distance between the probes. A 3D X-ray synchrotron tomography was used by Williams et al. [6] to obtain local measurements of crack growth in a 7075-T6 aluminium alloy. This instrumentation allows for *in situ* measurements of crack opening displacement (COD) but requires a suited precision alignment fixture for *in situ* testing.

In Kainuma's work [7], a quantitative examination of the efficiency of micro-encapsulated dye mixing paint was performed. This method allows for an easily applicable inspection also on actual structural components. However, it presents difficulty when detecting initial crack and short fatigue crack. The magnetic flux density around the fatigue crack was observed in the work of Tanabe et al. [8]. The magnetic flux was measured by means of a Magneto-Impedance sensor

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Nomenclature

ΔT	temperature increment = $T - T_0$
K	thermoelastic constant
σ_1, σ_2	principal stresses
α	coefficient of thermal expansion
ρ	density of the material
Cp	specific heat at constant pressure
A	thermoelastic calibration factor
S	infrared camera output signal
$\Delta\sigma$	stress amplitude
σ_a	stress semi-amplitude = $\Delta\sigma/2$
ω	frequency of loading
φ	phase angle between thermoelastic signal and loading
b_1	mean temperature rise
K_I	stress intensity factor (mode I)
K_{II}	stress intensity factor (mode II)
r, θ	polar coordinates measured from the crack tip
y	coordinate parallel to the line of the crack
S_{max}	maximum thermoelastic signal
N	number of cycles
da/dN	crack growth rate
C, m	Paris Law constants
ΔP	loading amplitude
B, W	characteristic dimensions of specimens according to Standard
a	crack length
$M(x, y)$	maximum value of thermoelastic signal
$[A]_{ixj}$	analysis area around the maximum value (M(x, y))
$[S]_{ixj}$	amplitude data matrix of thermoelastic signal
$[\Phi]_{ixj}$	phase data matrix of thermoelastic signal
$[\Phi n]_{ixj}$	normalized phase data matrix of the thermoelastic signal
$m(x, y)$	minimum value of phase signal

and a strong correlation was found with the stress intensity factor. However, this technique does not allow for an accurate crack length measurement.

Infrared thermography (IRT) was also proposed for the study of the fracture behaviour of materials subjected to fatigue loading [11–21]. 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. [11] 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. However, this procedure 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 aluminium alloys [22–25].

The aims of this work are: to propose an automatic procedure based on the Thermoelastic Stress Analysis (TSA) technique, to assess the Paris Law constants and to study, with the proposed procedure, the fracture behaviour of 4 stainless steels for which there is a lack of data present in literature.

Thermoelastic Stress Analysis (TSA), based on the thermoelastic effect, is a non-contact, full field technique that provides stress maps of a component subjected to dynamic loading [26–33]. In adiabatic and linear elastic conditions, a solid body subjected to a load undergoes a change of temperature proportional to the first stress invariant.

TSA technique can be used for the determination of the stress intensity factor during fracture mechanics tests [14–21]. 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 [14–21]. In particular, Tomlinson et al. [14,15] demonstrated the potential of TSA by using the amplitude of the thermoelastic signal for the crack tip and the SIF evaluation. In the works of Diaz et al. [16–19] the phase signal was proposed for detecting the crack tip position. In fact, phase changes of the signal are due to high stress gradients which may be ascribed to the non-adiabatic conditions and to the plastic behaviour of the crack tip. The characteristic performance of the phase signal at the crack tip contains a double reversal of sign, notably caused by the two cited effects which have the opposite sign influence [16–19]. In literature, phase signal is also considered as an effective parameter for the identification of local damage and for the evaluation of fatigue damage in materials [22–25].

This paper presents an automatable experimental procedure to characterize the fracture behaviour of steels and represents the completion of the works [20,21].