QIRT 2018
10.21611/qirt.2018.133
14th Quantitative InfraRed Thermography Conference

Energetic approach to study the plastic behaviour in CT specimens

by R. De Finis*, D. Palumbo* and U. Galietti*

* Politecnico di Bari, Viale japigia, 182-70126 Bari, Italy rosa.definis@poliba.it, davide.palumbo@poliba.it, umberto.galietti@poliba.it

Abstract

Thermography is very useful for characterising fracture mechanics behaviour of stainless steels. In this work, the technique is proposed for evaluating the intrinsic dissipations occurring in the plastic area around the crack tip in order to study the fatigue crack growth.

The existing experimental techniques involve accurate equipment and setup for assessing an estimation of the energy dissipated ahead the crack tip, in this way such the usability of these methods is restricted to just laboratory tests. Otherwise, the use of thermography based approach allows accurate analysis of energy variation occurring in a very localised area of the material. In particular, the adopted approach is based on thermal signal investigation in the frequency domain for separating the temperature values related to energy of dissipative processes that occur at twice the loading frequency.

1. Introduction

Among several techniques the most promising in the field of fatigue seems digital image correlation, useful to study the strain field of samples undergoing fatigue loadings [1] and Thermoelastic Stress Analysis (TSA), capable of detecting the damage in structures under cyclic load regimes [2].

In fact, the use of this experimental mechanics technique points to reduce the testing time, the experimental campaign costs and tends to optimise the mechanical characterisation of materials.

TSA is based on Infrared Thermography the contactless, full-field and non-destructive technique based on the assessment of the surface stress from temperature measurements. This is a promising technique also for studying the fatigue behaviour of materials [3-5] under different aspects: the aspect related to the study of initiation processes and the one related to the crack propagation.

Referring to the incoming of dissipative processes the most significant works are those provided by [6-8] where the energy was assessed both quantitatively and qualitatively by measuring second order temperature variations, and an estimation of the fatigue life is proposed.

In the field of Fracture Mechanics, infrared signal plays an important role to detect when and where the dissipative phenomena appear in order to reduce the time of experimental campaign. When the damage event is produced in a material, a localised heat dissipation appears and a temperature rise is recorded in that zone. In the specific field of fracture mechanics, a temperature rise is detected in the plastic zone around the crack tip where the plastic volume dissipates energy [9-12]. Therefore, thermography represents a valid tool to localise the crack tip that is important for both determining in experimental way, the Paris Law [13] as well as fatigue crack propagation [14].

When the crack is developed the behaviour of material depends on the intrinsic micro-mechanisms acting at the crack tip. The first authors that, proposed a relation between crack growth rate and stress intensity factor (SIF) were Paris and Erdogan [15-16] The Standards [17] provide conventional methods to assess the constants of Paris's Law by means of experimental non-destructive techniques [1], [11-13] [18].

Other approaches [14], [19], the dissipated energy at the crack tip was be directly related to hysteresis loop [20], and a Paris' law based on these measurements was determined in the Klingbeil's [19] approach.

In the work of Meneghetti et al. [21], the specific heat energy per cycle for a small volume material was assessed by measuring temperature variations during experimental tests. However, the just exposed procedure finds limitations each time the temperature changes are low (short cracks for brittle materials [21]), this issue requires high-performance equipment and specific setup.

The TSA approach is quite different, since it requires a simple setup but an in depth understanding of the phenomena in the crack tip region by measuring the temperature variations. Interesting results were achieved in the field of the assessment of plastic zone and SIF [22]. In fact, the assessment of sum of the stress in principal directions it is possible to full characterize the SIF while the analysis of the thermoelastic phase data allows for crack growth rate determination. In this regard, Ancona et al. [13] proposed an automatic procedure based on TSA, to assess the Paris Law constants and to study the fracture behavior of four stainless steels.

In this work, it will be shown as the infrared signal produced by dissipative heat sources can be used for estimating the heat dissipated in cyclic plastic zone, and then for evaluating the crack growth rate. In particular, the amplitude of the thermal signal at the twice of loading frequency has been used as an index of the heat dissipated. In order to better understand the phenomena, provided by the adopted approach the phase of thermal signal was used to support in localising the dissipative phenomena. In fact, the phase of thermal signal allows discerning two different phenomena: the

plastic behaviour and the crack closure effect. In fact, it will be demonstrated as these effects are not-in-phase each other and the crack tip is obtained in correspondence of a phase signal equal to zero.

The material considered was AISI 422 and three Compact Tensile (CT) samples were tested. An Infrared cooled detector was used for continuous monitoring the crack tip evolution. The thermographic data were furtherly processed in frequency domain to extract the amplitude signal related to heat dissipated at the crack tip. This index was used to determine the crack growth rate during the fatigue test.

2. Theory

Different authors found that in presence of a dissipative phenomenon such as a crack, in a material undergoing a cyclic loading, it is possible to define the plastic volume which, dissipates energy around the crack [23-25].

By considering a finite control volume '*V*' containing the plastic area 'A_p', round shaped [26], characterised by its radius 'r_p' around the crack tip, the first law of thermodynamics gives:

$$W_p = \oint \sigma_{ij} d\varepsilon_{ij} = Q + E_d + E_p \quad (1)$$

In Eq. (1) the mechanical energy per cycle 'W_p', related to the area under the hysteresis loop can be split in 'Q' which represents the heat exchanged per cycle by the body during the fatigue test by convection, conduction and radiation; the term 'E_p' that refers to portion of internal energy used to deform and to change irreversibly the material morphology and the term 'E_d' representing the energy per cycle dissipated as heat, related to plastic or viscous phenomena.

The sum of these latter contributions represents the internal energy due to the irreversible microstructural phenomena such as dislocation movements. A portion of this energy participates to the irreversible heat sources development in the material, then it switches into temperature variations [27].

'E_d' is proportional to the total energy dissipated at the crack tip and it is used in this work to investigate the crack growth behaviour.

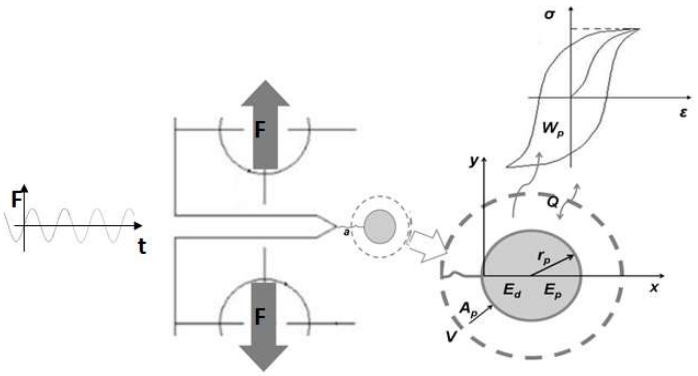

Fig. 1. *Representation of the plastic zone and energy contributions at the crack tip during cyclic loading.*

By considering a bilinear hysteresis loop where kinematic and isotropic hardening phenomena are neglected Figure 2, at stress ratio of R=-1, for sake of simplicity. Until the load is elastic, the behaviour of material is described by a full recovery of elastic energy per cycle and irreversible dissipative sources are zero [23]. The cyclic loading produces a delay between strain and stress involving the occurrence of the hysteresis loop. In presence of plastic phenomena, due to increase two time per loading cycle of the plastic deformation, a portion of the total mechanical energy is converted in heating two times per cycle during both the tensile loading (a'-b) and the compression loading (c'-d), figure 2.

By assuming:

- the major part of the energy is dissipated as heat,
- the absence of heat exchange to/from environment (Q=0),
- the linear increase of 'E_d' from a' to b, and c' to d points of diagram [28], figure 2,

the temperature rise in the plastic zone occurs two time per loading cycle, and generally, it tends to increase cycle after cycle. However, in presence of heat exchanges (Q≠0), the temperature increases until a steady state value is reached [24].

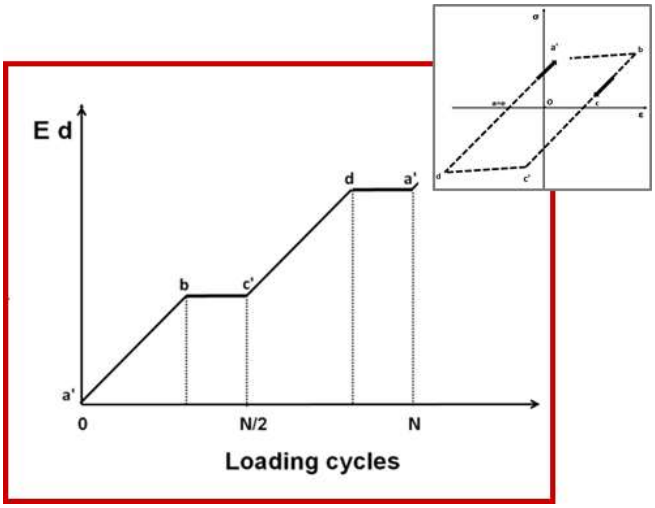

Fig. 2. *Trend of the heat dissipated energy Ed in a unit volume of material in a loading cycle related to a simplified model of the hysteresis loop (stress ratio R=-1).*

In next sections, it will be shown the experimental set-up and methods used for evaluating the heat dissipated per cycles during the fatigue test.

3. Experimental setup

The AISI 422 material is a variant of AISI 420, it conserves the same quantities of Carbon and Chromium, but the addiction of Mo, V, and W, makes possible the precipitation of complex carbides, which strengthen the matrix. The material, in fact, can be aged at 650°C, without reducing mechanical properties.

The ultimate tensile strength is 100 kg/mm2 (elongation 18%), the properties are slightly lower than the 420 series. Moreover, the presence of Chromium enhances the resistance at creep and makes the material useful at high temperature (close to 650 °C) operative conditions [29]. The ultimate tensile strength is 966 MPa, the yield strength is 760 MPa.

In table 1 are presented its chemical composition [30].

Table 1. *Chemical composition of AISI 422*

%wt									
C	**P**	**Si**	**Ni**	**V**	**Mn**	**Cr**	**S**	**Mo**	**W**
0.20-0.25	0.025	0.4	0.50-1.00	0.15-0.30	1.0	11.0-13.0	0.025	0.75-1.25	0.75-1.25

The samples tested were compact tension type sized according ASTM E 647 [17]. Dimension are reported in mm, in figure 3a, furtherly a thin coat of matt black was applied to the specimen for increasing the efficiency of thermographic measurements and it was fixed on the loading machine grips, figure 3b.

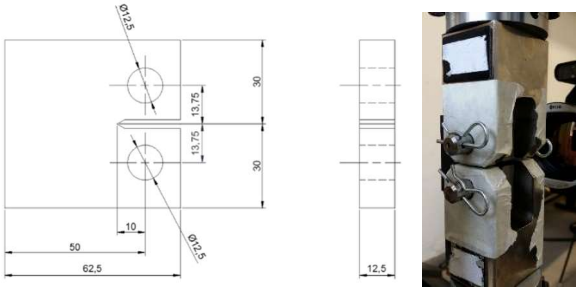

Fig. 3. Geometry of CT sample (a) gripping system of coated sample (b).

The standard [17] reports also, the test execution procedure. In particular, a constant-force-amplitude procedure was applied, the constant force range was ΔP=10.8 kN, the stress ratio was R=0.1 and loading frequency was 13 Hz.

An infrared cooled InSb detector FLIR IR X6540 SC providing a 640x512 pixels matrix, acquired sequences at constant intervals of 2,000 cycles at 123 Hz. The infrared thermal camera was positioned in front of the sample, figure 4.

Due to proximity of the infrared detector to the sample (170 mm of distance), the geometrical resolution was 0.067 mm/pixel. The detector was equipped with a 50 mm lens with a 12 mm extension ring.

Before performing the test, all specimens were pre-cracked until to reaching a crack length of 2.5 mm according to ASTM E-647.

Fig. 4. Setup and equipment.

4. Data processing

In previous sections it has been shown as the energy increase 'E_d' occurs, two time per cycle due to the double increase of the plastic deformation during hysteretic behaviour of material. The way to detect this energy is by measuring the temperature changes while the test is running. In fact, the temperature signal variation, related to this energy variation ('S_d'), clearly occurs at twice the mechanical loading frequency [28], [31] as shown in figure 5.

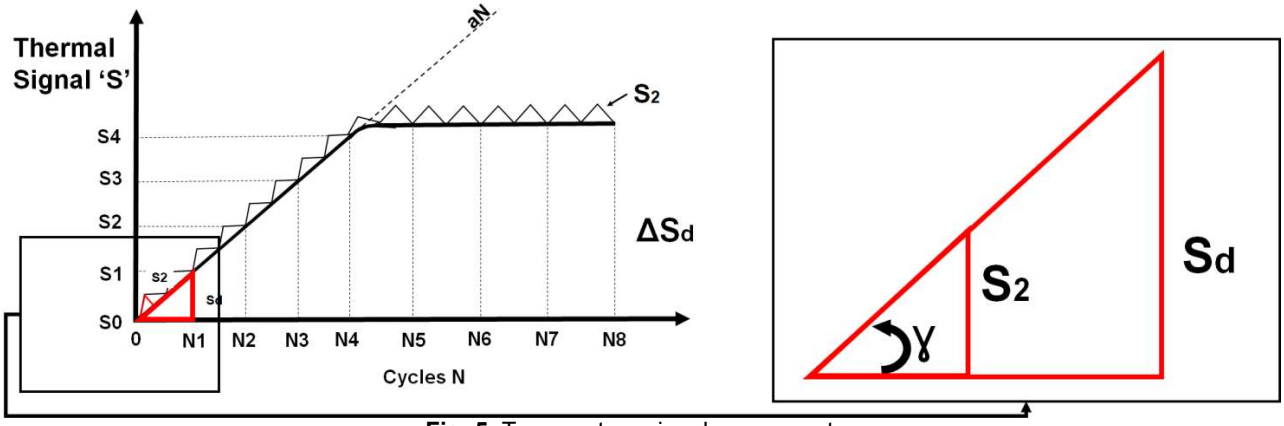

Fig. 5. Temperature signal components.

In particular, figure 5 reports the temperature signal decomposed in three specific contributions:

- The offset 'S_0' representing the environmental temperature influences, supposed constant between different loading levels,
- a linear temperature increase, dS/dt with a slope '*a*' over the number of cycles,
- the signal amplitude 'S_2' which period is equal to (1/2)N, representing the periodic part of 'S_d'.

The relation between 'S_d' and 'S_2' is geometrically represented in figure 5.
The periodic component of temperature signal ('S_2') can be supposed varying with a triangular function pulsating at $\omega_0=2\omega=2(2\pi f)$, then its Fourier series expansion become:

$$\boldsymbol{S(t)} = \frac{\boldsymbol{S_2}}{\boldsymbol{2}}\boldsymbol{A}\sum_{\boldsymbol{1}}^{\infty}\frac{\boldsymbol{1}}{\boldsymbol{(2n+1)^2}}\boldsymbol{cos(2n-1)\omega_0 t} \quad (2)$$

Where the constant 'A' is equal to:

$$A = \frac{4S_2}{9\pi^2} \quad (3)$$

By imposing n=1, and excluding high order terms, eq. 2 becomes:

$$\boldsymbol{S(t)} = \frac{\boldsymbol{S_2}}{2} + \boldsymbol{Acos}2t\boldsymbol{\omega_0} \quad (4)$$

The equations form (2) to (4) show as the amplitude 'S_2' can be used as index to estimate the heat dissipated at the crack tip region. This index can be evaluated by processing the thermal signal in the frequency domain by using a suitable model:

$$\boldsymbol{S(t)} = S_0 + \frac{a}{f}N + Bsin\left(\omega\frac{N}{f} + \varphi_1\right) + Acos(2\omega\frac{N}{f} + \varphi_2) \quad (5)$$

where '*f*' is the mechanical loading frequency, '*N*' the loading cycles, $Bsin\left(\omega\frac{N}{f} + \varphi_1\right)$ is the term describing the effect of first order such as the thermoelastic temperature signal variations [31], describing the dependence of the temperature from the elastic properties of the material, and $Acos(2\omega\frac{N}{f} + \varphi_2)$ is the term most involved in the dissipative phenomena occurring in presence of irreversible energy production. It is worth noting that even if heat exchanges cannot be neglected, the A term allows an estimation of the heat dissipated. In the model which provides several indexes to study entirely the components of the thermal signal, appear also the phase shifts φ_1 and φ_2, that in turn represent the thermoelastic phase shift [9] and the phase shift between first and second order harmonic components. Both these two parameters are correlated to local dissipative damage [31], however, it is not in the purpose of the present paper to use these parameters, since they allow for determining the when and where a dissipative process occurs but not to measure the relative energy variation.

In this work, the attention will be focused on the study of 'S_d' and '$\varphi_{2\omega}$'. In particular, it will be demonstrated as a similar Paris Law model was obtained between the crack growth and 'S_d'.

5. Results: Determination of the crack growth by means of S_d

In this section the results about the analysis performed on thermographic sequences acquired each 2000 cycles of the loading machine during the test is discussed.
The results refers as specified to the parameter S_d which is the component related to irreversible dissipative processes occurring at the twice of the loading frequency.
As explained in the theoretical part, when a plastic process hit the lattice, an energy generation occurs and then the temperature rises. In fracture mechanics, this occurs ahead the crack tip, due to plastic volume dissipations. However, as already exposed, this heat can be lost because of heat exchanges for conduction, convection and radiation.
In the region affected by irreversible processes, another significant effect is represented by the crack closure region which makes the estimation of the crack tip difficult [32]. In this region, the facets of surfaces damaged get in contacts

each others producing a multispectral signal, which sums up to the energy generation due to high plasticization stresses [11].
In fact in figure 6 two separated zones A1 and A2 can be detected, related to these phenomena. As shown in Figure 6 these zones clearly appear until high values of the crack length and SIF were reached. In fact, as the crack length growths, the crack opening increases also and the effect of the crack closure is less significant.

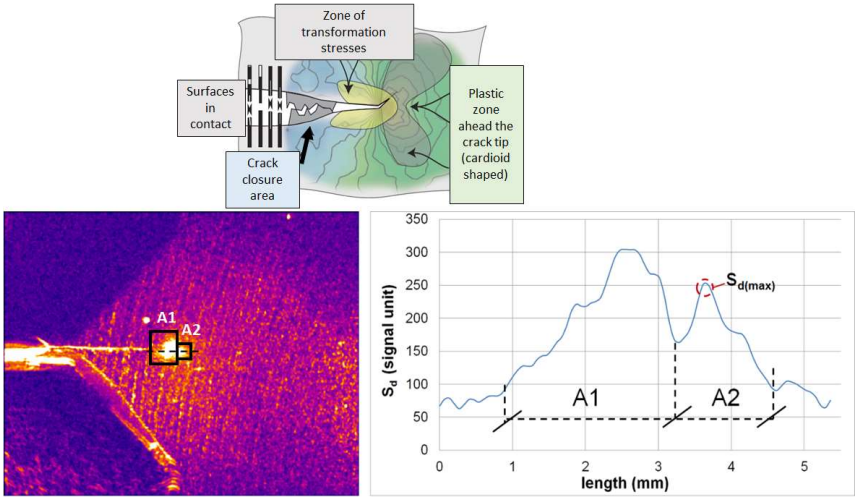

Fig. 6. Crack closure effect (A1) and Plasticisation area (A2).

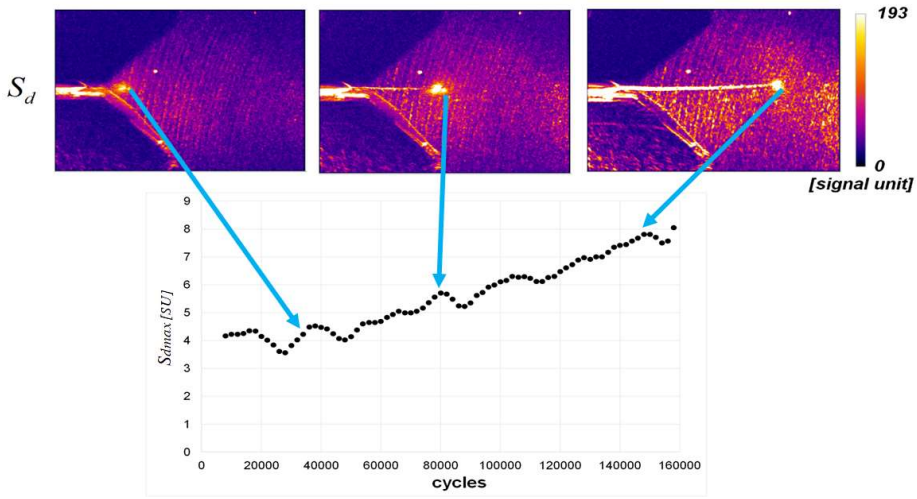

Fig. 7. S_d signal in the A_2 area during the test.

By considering a controlling area around the region A2 (Figure 6), the maximum value of S_d (S_{dmax}) can be evaluated each 2000 cycles, as reported in Figure 7 for specimen 1. In this way, the only energy dissipation related to the real fatigue dissipating area are assessed.

The fact that the maximum of temperature signal (S_{dmax}) increases, suggests the same behaviour as the crack growth increase toward loading cycles. In fact, the twice per loading cycle temperature variation is correlated to the energy of irreversible processes, so that it can be used for describing the crack propagation. A relation between da/dN and energy is possible, in fact, other authors found and verified the model between the dissipated hysteretic energy per cycle in place and crack growth rate [14].

In figure 8, three samples have been used for building the model relating the S_{dmax} values compared to the crack growth rate values obtained in a previous work [13] during the same test. A linear relation can be determined between these two parameters:

$$da/dN = aS_d{}^b \tag{6}$$

Eq. 6 can be used for evaluating the crack growth rate by knowing the thermal signal S_{dmax} ahead of the crack tip. To do that, in this work, as reported in figure 8, the thermographic data of the three samples have been used for evaluating the coefficients 'a' and 'b' then, the linear model has been used for predicting the crack growth rate of the specimens 1 and 2.

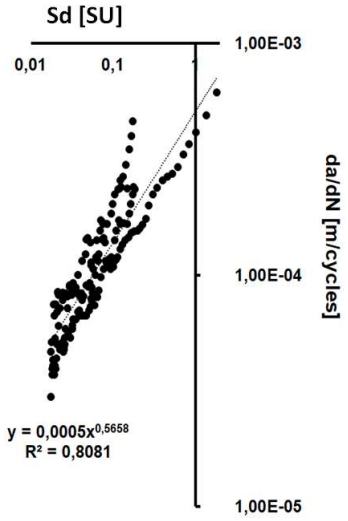

Fig. 8. Relation between second order temperature variation related to damage at the crack tip (S_d) and crack growth rate da/dN.

Results are reported in figure 9, and compared with the crack growth rate measured with TSA technique [13] of one of the three samples. In figure 9, the crack growth rates are reported as function of the evaluated values of ΔK_I according to Standard ASTM E 647 [17].

In figure 9, is shown the good agreement between the assessed and measured data.

Further works will be focused on the determination of the heat dissipated per cycle at the crack tip by considering calibrated temperature data in order to verify the analytical and numerical models present in literature [14], [19].

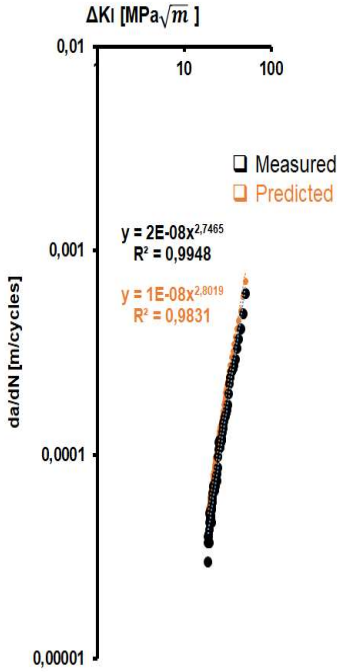

Fig. 9. Comparison between the crack growth rate values obtained with eq. 10 and with TSA [7] .

CONCLUSIONS

In this paper, the thermographic technique has been used to evaluate the crack growth rate of AISI 422 during fracture mechanics tests. In particular, the thermal index directly correlated to the heat dissipated at the crack tip was used: the amplitude (S_d) of the thermal signal that changes at the twice of loading frequency.

Three CT specimens were tested and monitored by means of a cooled infrared camera in order to acquire thermographic sequences during tests at regular intervals (each one of 2,000 cycles). A similar Paris Law model was obtained between the crack growth and S_d. Moreover, it was demonstrated as this relation can be used for predicting the fatigue crack growth after a previous calibration procedure.

The further developments of the technique will addressed to the assessment of the calibrated signal in order to obtain the heat involved in the plastic zone, and not only its estimation.

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