Study of the plasticity effect at the crack tip in Titanium by using thermal signal analysis

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Abstract

The fatigue crack growth is strictly related to the dissipated energy at the notch/crack tip. Among the different approaches developed, those focusing their attention on energy dissipated in the plastic area seems to be more promising in the evaluation of the crack growth behaviour and it can be used to describe the plastic work at the crack tip. In this work, an experimental approach was adopted in order to obtain thermographic parameters capable of describing the plastic work at the crack tip. In particular, the influence of tests parameters such as the loading frequency, has been investigated.

1. Introduction

The process of crack growth is affected by the energy dissipated at the notch/crack tip. In effect, in literature different analytical and numerical models [1-3] were proposed by researchers to describe as the plastic work affects the fatigue behaviour.

In recent years, researchers focused their attention on energy-based approaches [5-7] as the dissipated energy plays a key role in the crack growth behavior and it can be used to describe the plastic work at the crack tip [8-9]. The energy-based approach proposed firstly by Weertman [1], links the crack growth rate with the critical energy to create a unit surface area. Mazari et al., [3] starting from the Weertman's and Klingbeil's [2] approaches, developed a new model in which a similar Paris Law model was obtained between the crack growth and the heat dissipated per cycle.

In this experimental work thermoelastic and thermal parameters, capable of describing the plastic work at the crack tip, were used for studying fracture mechanics of pure titanium small scale samples. Moreover, the influence of loading frequency was investigated too.

2. Theory

The thermal signal analysis is performed by acquiring the thermal response of components and samples undergoing dynamical loads.

For a homogenous and isotropic material, the calibrated thermographic signal T during a fatigue test, can be written in the time domain as [10]:

$$T(t) = T_0 + at + T_1 sin(\omega t + \Phi_1) + T_2 sin(2\omega t + \Phi_2) \tag{1}$$

The second term in Eq.1 represents the increase in mean temperature T_0, whose linear growth with the time is defined through the coefficients a which depends on the physic characteristics and geometry of the component. This term is affected by the heat transfer (conduction in the specimen or convection and radiance to the environment).

The application of a sinusoidal load with a sufficiently high frequency, make the heat transfer negligible and the Fourier harmonic components can be experimentally measured performing a lock-in analysis of the signal.

The third term in Eq.1 is the thermoelastic component, varying at the same angular frequency as the load; T_1 and φ_1 are respectively the amplitude and phase of first harmonic amplitude component of Fourier. The phase Φ_1 represent the delay between the load and the thermal response and under adiabatic conditions it is constant throughout the component but it varies if the adiabatic condition is no longer respected; this could be the case of high stress gradients, which lead to conduction effects [11,12] or heat generation due to local plasticity[13, 14].

The amplitude T_2 and phase Φ_2 of the second Fourier harmonic components, are the result of two effects both occurring at the twice of the loading frequency: the thermoelastic response due to the second order effect [15,16] and the temperature variation due to dissipation[17].

Referring to the amplitude, when local plasticization effects occur, the thermoelastic component is at least one order of magnitude smaller than the second and therefore it can be neglected, in this case, the measured T_2 can be considered only related to the energy dissipation due to plasticization.

The capability of these parameters in fracture mechanics behaviour assessment was demonstrated by several authors [8,10.]. In particular, the amplitude T_2 allows the evaluation of the plastic and crack closure areas [8] while the phase shifts Φ_1 [10] and Φ_2 [8] are used to localise the crack tip [10].

In the present work, $T_2 \Phi_1$ and Φ_2 are used to study the influence of the loading frequency on the thermal footprint of the plastic area ahead the crack tip.

3. Experimental campaign and Signal processing

In this work, small scale compact tension specimens made of pure grade 2 Titanium were tested. The sample geometry is reported in figure1, while the material characteristics are reported in table 1

Table 1. Pure Titanium mechanical characteristics

Young modulus, E	105 GPa
Yield strength, σ_y	390 MPa
Ultimate tensile strength, σ_u	448 MPa

The tests were carried out by using a loading frame MTS model 370 with a 25 kN of capacity (figure 1). According to ASTM E 647, the test procedure involved constant-force-amplitude load at stress ratio R=0.1. The sample was pre-cracked by applying loading cycles with the frequency of 17 Hz, a maximum load of 750 N and R=0.1 until the crack did not reached a length of about 3 mm (after 21000 cycles). The thermographic acquisitions were performed every 2000 cycles with a maximum load of 400 N, R=0.1 and different loading frequencies, ranging between 8 and 23 Hz. The experimental campaign characteristics are reported in table 2.

Table 2. Experimental campaign

N° of cycles	F_{max} [N]	R	frequency [Hz]	N° of acquisitions
23000			17	3
25000			8	3
27000			10	3
29000			13	3
31000			15	3
33000			17	3
35000			19	3
37000			21	3
39000	400	0.1	23	3
41000			8	3
43000			10	3
45000			13	3
47000			15	3
49000			17	3
51000			19	3
53000			21	3
55000			23	3

Thermographic sequences were acquired during tests by adopting the cooled detector of FLIR IR X6540 SC IR camera at a frequency of 200 Hz. A geometrical resolution of 0.0352 mm/pixel was adopted for the crack monitoring. Figure 1 shows the setup and equipment.

Referring to equation 1, a mathematical algorithm implemented in IRTA® software was used to extract pixel by pixel, the phase angle and the amplitude of the first and second Fourier harmonics of the thermoelastic signal. Data are calibrated in temperature, assuming for the black painted surface an emissivity of 0.95.

To compare the minimum Φ_1 and the maximum T_2, the 2° percentile and the 98° percentile were respectively evaluated in an area extracted around the crack tip.

In order to reduce the noise, T_2 and Φ_2 maps where filtered using a Gaussian filter, while the data used to plot T_2 and Φ_2 horizontal profiles have been smoothed by applying a moving-average filter with a radius of 5 pixels.
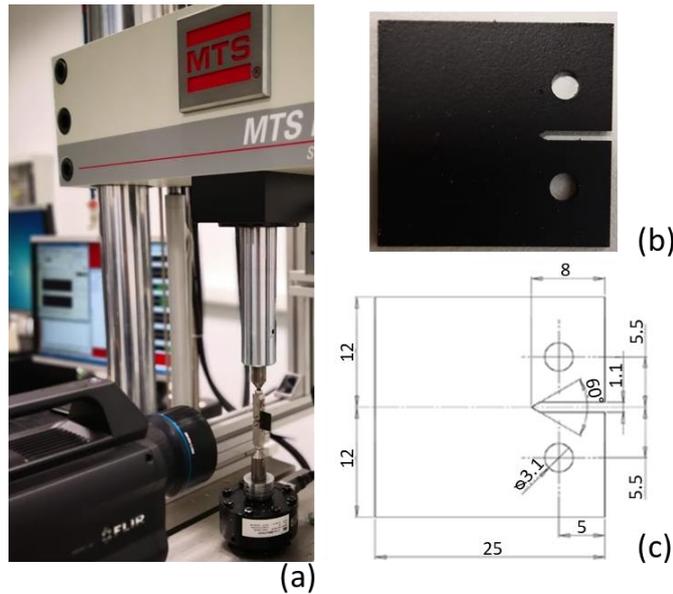
Fig. 1. *(a) Setup and equipment. The sample face used for the TSA acquisitions was painted with a black mat spray (b). The measures are reported in mm (c)*

4.   Results and discussion

Figure 2 shows the results in terms of maps of $\Phi 1$, $T2$ and $\Phi 2$ at the crack tip for the loading frequency of 8 Hz, 17 Hz and 23 Hz of the area around the crack tip considered in this analysis.

The Φ_1 and Φ_2 data have been re-phased by subtracting the mean value evaluated in an area of the sample whose stress field is not affected by the crack during the loading.

For the two phases, the areas and the absolute value at the crack tip interested by the heat source due to the plasticity decrease when the frequency increases. The area and the absolute value of the amplitude T_2, instead is lower at 17 Hz.

These trends are confirmed in In Figure 3, where the 2° percentile of the phase signal and the 98° percentile of the thermal signal are reported; while the former increases monotonically the latter stabilizes, being highly affected by the noise at around 15 Hz.

In Figure 4, 5 and 6 are plotted the values of Φ_1, T_2 and Φ_2 along a horizontal profile parallel to the crack and passing for the crack tip for all the frequencies.

The comparison between the horizontal profiles gives information about the potential of the TSA in describing the area around the crack tip which is locally plasticizing. The Φ_1 horizontal profiles show how the phase area affected by the non-adiabatic conditions (which imply a non-null phase value) decreases with the frequency but it seems to stabilize at roughly 17 Hz.

From Figure 4, considering only the frequencies 17, 19, 21 and 23 Hz it is possible to infer the crack tip position between the pixels 520 and 521 (range of 1 pixel, corresponding to 0.0352 mm), which is the point of sign-inversion of Φ_1. At 8 Hz the point of sign inversion is shifted of 4 pixels (0.14 mm) on the right.

The point at which the first phase returns to zero can be related to the plastic zone extent but it is also influenced by conduction effects, which imply its variation with the loading frequency. In effect, the length of the negative section varies from 37 pixels (1,3 mm) at 23 Hz to 46 pixels (1,62 mm) at 15 Hz and to 65 pixels (2.29 mm) at 8 Hz.

The comparison among the T_2 horizontal profiles (Figure 5) and the Φ_1. horizontal profiles (Figure 4), shows how the pixels characterized by a negative Φ_1 present an increase of the amplitude T_2, which is higher than the average value measured in the elastic area. The section on the right of the crack tip is interested by a maximum signal value, that the authors attribute to the crack closure [8], a dissipative phenomenon where the opposing faces of a crack remain in contact during the loading, occurring at twice of the loading frequency.

The crack closure effect is also evident in the Φ_2 horizontal profiles on the right side of the red dashed line indicating the crack tip position in Figure 6. All the frequencies show a higher value at the crack interface.

The area ahead the crack tip is instead characterized by Φ_2 negative values, however the phase variation is not high enough to be distinguished from noise.
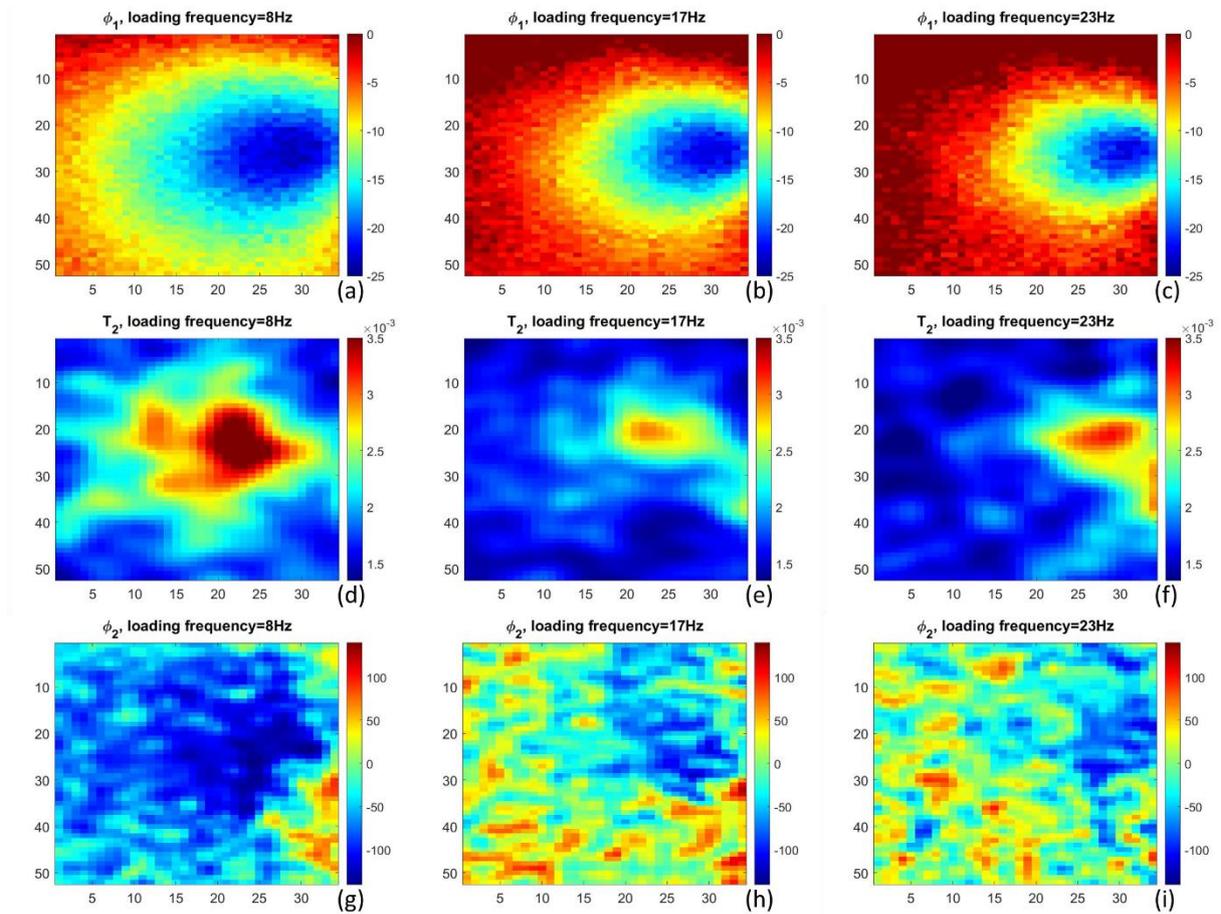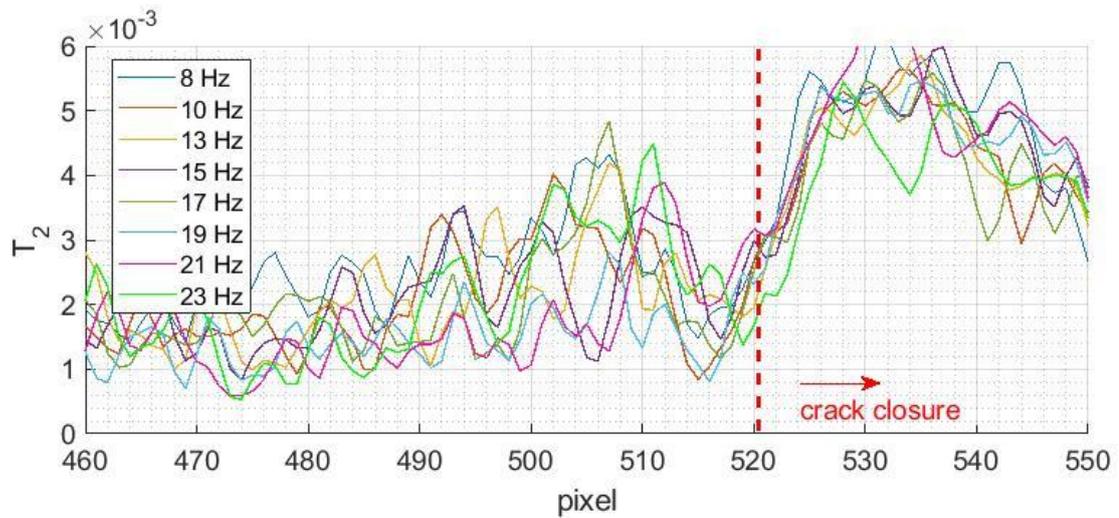
Fig. 2. *Φ_1 at the crack tip for the loading frequency of 8 Hz (a), 17 Hz (b) and 23 Hz (c), T_2 at the crack tip for the loading frequency of 8 Hz (d), 17 Hz (e) and 23 Hz (f) and Φ_2 at the crack tip for the loading frequency of 8 Hz (g), 17 Hz (h) and 23 Hz (i)*
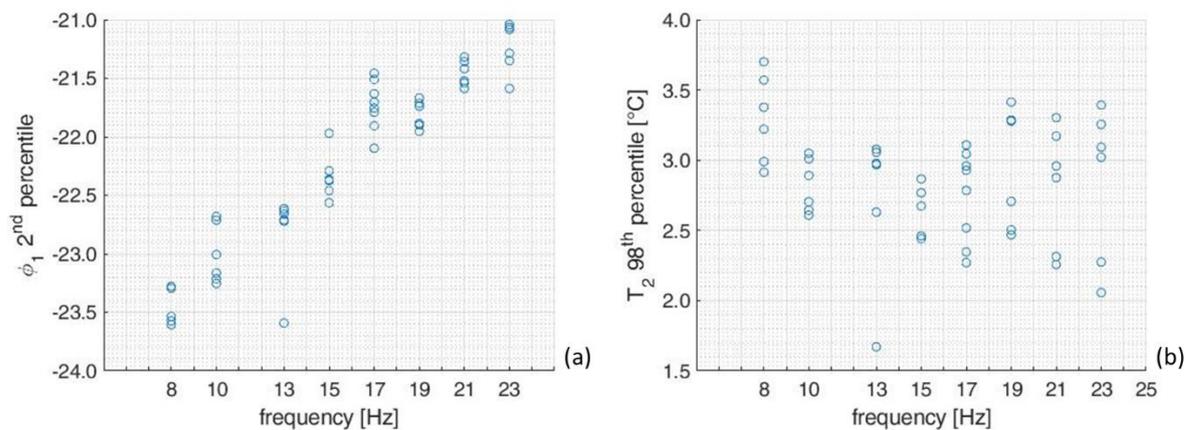

Fig. 3. *a) 2nd percentile of the phase signal and b) 98th percentile of the T_2 as function of the loading frequency*
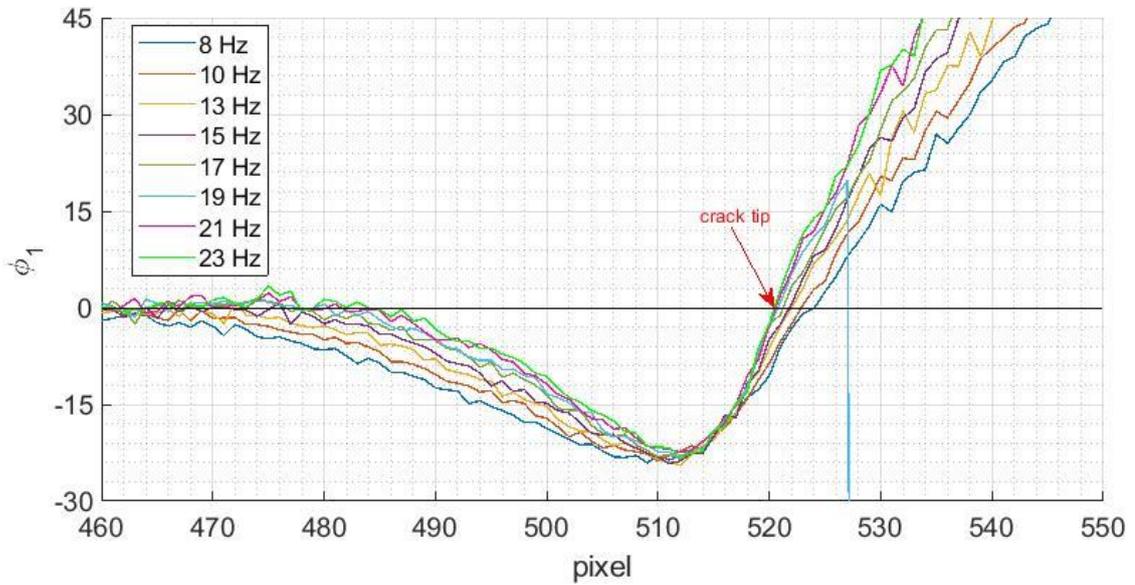
Fig. 4. Φ_1 along a horizontal profile parallel to the crack and passing for the crack tip for all the tested loading frequencies

Fig. 5. T_2 along a horizontal profile parallel to the crack and passing for the crack tip for all the tested loading frequencies. The maximum reached at the left of the red dashed line is due to the crack closure effect.
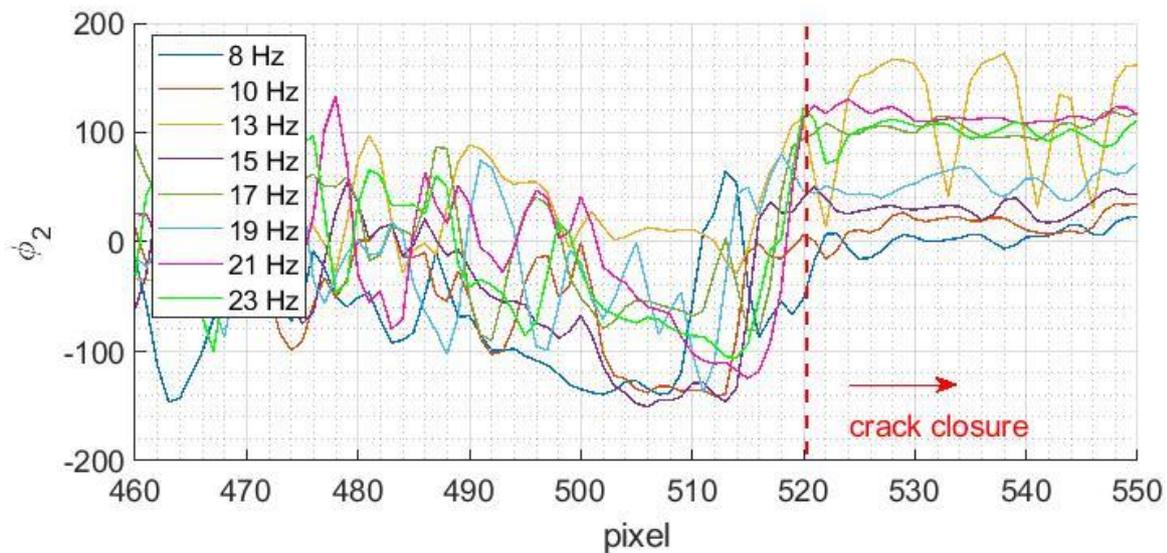
Fig. 6. *Φ_2 along a horizontal profile parallel to the crack and passing for the crack tip for all the tested loading frequencies. The maximum reached at the left of the red dashed line is due to the crack closure effect.*

5. Conclusions and Outlooks

In this work the parameters T_2 Φ_1 and Φ_2 which characterize the thermal response of a cracked Titanium CT samples under a cyclic load at different frequencies were studied in order to relate them to the plastic area ahead the crack tip.

The experimental tests showed the following results for the three parameters:

- The parameter Φ_1 presents absolute values and an area of sign inversion which decrease with the frequency; However, the difference is smaller at the higher frequencies. In the frequency range 17-23 Hz, the point of sign inversion localizes the same crack tip position, while at 8 Hz the point is shifted of 0.14 mm.
  Considering the horizontal profile passing for the crack tip and parallel to the direction of the crack propagation, the extent of the sign inversion zone passes from 1,30 to 2,9 mm.

- The parameter T_2 presents absolute values and the area with values above the elastic zone average signal which decrease with the frequency up to 15 Hz. From 15 to 23 Hz the trend reverses and both the absolute values and the area increase with the frequency, but the trend is not clear due to the high noise value.

- The data obtained for the parameter Φ_2 are difficult to interpreter due to the noise. However, it is possible to estimate a common trend which is characterized by a sign inversion ahead the crack tip.

Both the T_2 and Φ_2 maps prove the presence of the crack closure which appears as an increase of both the parameters.

The strong dependence of the results on the frequency could indicate that conductive phenomena interfere with dissipative phenomena which are more important at low frequency. To relate the thermal parameters to the dimensions of the plastic zone around the crack tip, the material thermal-physic characteristics and all the heat sources should be considered, including the crack closure contribution.

Further work will imply the comparison of the experimental results with the study of the thermal behaviour of the Titanium cracked CT sample through a FEM analysis, by simulating all the heat sources involved. Furthermore, a procedure to evaluate the plastic zone extension will be studied by comparing the plastic zone shape and dimension with results obtained with method based both on Digital Image Correlation and theoretical models.

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