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Fatigue Damage Monitoring by means of Acoustic Emission and Thermography in Ti grade 5 specimens

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Abstract

In this paper the crack propagation process in Titanium grade 5 specimens subjected to uniaxial fatigue loading was studied by adopting two different non-destructive technique (NDT) namely Acoustic Emission (AE) and Thermography. A couple of sensors placed on the sample and acoustically coupled with the metal through a coupling gel allowed to detect elastic waves produced inside the sample as a consequence of activation of inner defects. Part of the overall acoustic activity can be directly referred to the crack propagation process. At the same time the superficial temperature of the specimens was continuously monitored during the whole test to detect variation in temperature in the sample. In particular the rise of temperature around the crack tip was monitored in order to evaluate the advancing of the crack during the test. Finally the two methods were compared in order to underline differences in capability of predicting incumbent catastrophic failure.

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Keywords: Acoustic Emission; Fatigue; Titanium grade 5; Crack Propagation; Thermography

1. Introduction

Nowadays great interest is present in many engineering fields such as aeronautics, automotive or biomechanics in a wider adoption of Ti alloys. In general, this class of material is appealing wherever weight savings and space limitations issues must be afforded [1]. Furthermore Ti alloys maintain good mechanical performance at high

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temperature and the specific alloy (Ti6Al4V) studied in this paper can be successfully used up to 400 °C [2]. Of course fatigue characterization is a very important topic to allow safe design of structural parts made by Ti alloy and a relevant number of works can be found in scientific literature on this topic [3-9]. However the alternative methods of analysis of Ti sample subjected to fatigue can help in understanding the behavior of these alloys and it is a topic that requires further investigation. In this framework acoustic emission (AE) technique appears to be an unique method to evaluate the internal status of the sample through the detection of the internal stress waves [10-11] connected with defect activity [12] and its use has been successfully explored in many different applications including thermal loading [13-16] and mechanical loading [17-20]. Additionally also infrared thermography (IR) is widely used for the analysis of different damage modes [21]; fatigue damage, in fact, is an irreversible process in which part of the total energy is dissipated in heat which contributes to local rising of the temperature; being IR a full-field technique this also allows damage localization. Also AE allows localization of the damage through triangulation of more sensors placed upon the samples. A common benefit shared by both the techniques is that they allow continuous monitoring [22] of the structure without the necessity to stop the test and unclamp the specimen. In this paper a comparison among the data from both AE and IR techniques is provided and indications about their capability of following damage evolution in Ti grade 5 samples under uniaxial fatigue loading is discussed.

Nomenclature

A	Cross section of the samples
l	Length of the samples
r	Radius of the slots
k_t	Stress Concentration Factor
R	Loading Ratio
σ_0	Applied nominal stress
f	Loading Frequency
d	Distance between the sensors
V_{th}	Threshold Voltage
v	speed of the acoustic wave
d_{1y}	Longitudinal distance of the acoustic event from the sensor 1
d_{2y}	Longitudinal distance of the acoustic event from the sensor 2
ε	Emissivity coefficient
T_1	Arrival time of the acoustic wave on the sensor 1
T_2	Arrival time of the acoustic wave on the sensor 2
d_c	Distance of the thermocamera
f_c	Acquisition frequency of the thermocamera
Ñ	Normalized number of cycles

2. Materials and Methods

The samples tested in this work were laser cut by a Titanium grade 5 sheet (Fig. 1). The samples had a rectangular cross section A=40x4 mm^2 and a length l=200 mm. In order to introduce a stress concentration area in the sample, two notches were cut having a radius r=5mm. The stress concentration corresponding to this geometry was computed by FEM analysis and it was found to be k_t=3. Fatigue tests were performed, under sinusoidal fully reversible loading, by an Instron servo-hydraulic machine equipped with a 200 kN loading cell. Three different levels of stresses were tested, respectively σ_0=125 MPa, σ_0=150 MPa, σ_0=300 MPa with a loading ratio R= -1 and a loading frequency f=3 Hz. Two piezoelectric Pico sensors [23] were placed in the upper and in the lower part of the sample symmetrically with respect to the median axis of the sample (Fig. 2). The distance between the two sensors was d=80 mm.

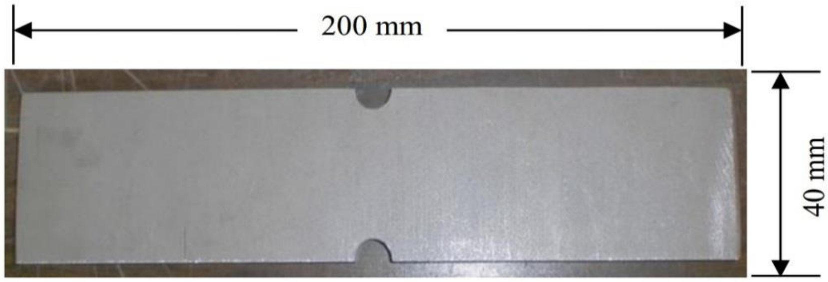

Fig. 1 Geometry of the Ti grade 5 tested samples.

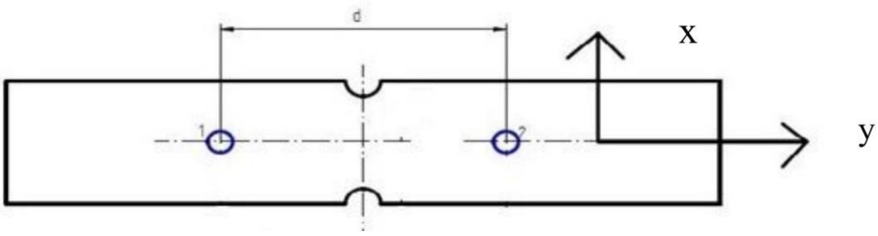

Fig. 2 Disposition of the AE sensors on the specimen.

Signal from the sensors is sent firstly to a 40 dB preamplifier and successively to the acquisition board. The acquisition software was set to acquire only signals which overpass a threshold value V_{th}= 45 dB. The speed wave velocity was set to the value v=5500 m/s. This allows, through triangulation of the signals recorded by the two AE sensors to detect the linear position of the acoustic event by solving the following:

$$|d_{1y}-d_{2y}|=v\cdot|T_1-T_2| \quad (1)$$

and

$$d=d_{1y}+d_{2y} \quad (2)$$

AE signals were recorded and elaborated by PAC software. IR thermography was performed by a NEC H2640 thermocamera placed in front of the sample at a distance d_c=55 cm (Fig. 3). This instrument has a resolution of 640 x 680 pixel and was set to acquire at f_c=30 Hz. Thermographic images were continuously transferred to the control PC through the IEEE 1394 interface by using the Unifizer software while the data elaboration was performed by the InfReC Analyzer Lite software. In order to obtain homogeneous and known emissivity of the sample and to avoid artifacts connected with reflections, the sample was preliminary painted by a black matt spray paint having an emissivity coefficient ε=0.97.

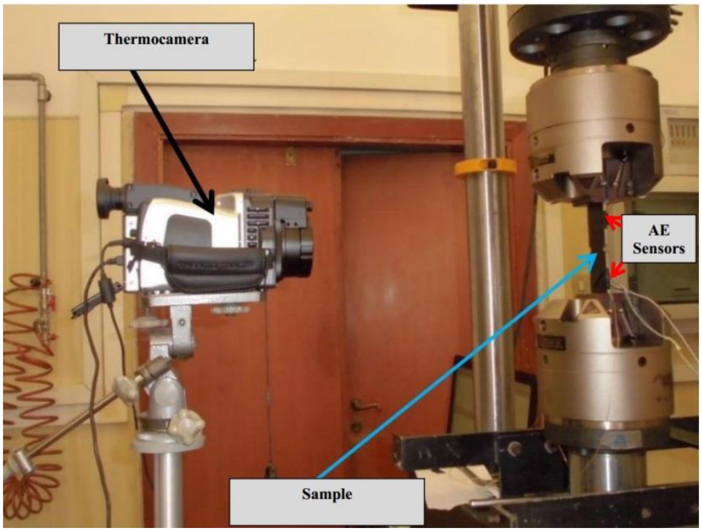

Fig. 3 Picture of the experimental set-up including the thermocamera and the AE sensors.

3. Results and Discussions

In Fig. 4 it is possible to observe a sequence of three thermal images recorded at different stages of the fatigue test. From left to right in clockwise direction it is possible to see that the crack tip appears to be identifiable in the first image as a small temperature increase with respect to the surrounding area (see the black arrow), while continuing the test the temperature in the surrounding of the crack increases more and more so that the crack tip becomes easily detectable as it can be observed in the second picture and even much more the third picture which is very next to the final rupture. Capability to precisely identify the position of the crack tip is evident by observing the figure and it is a natural consequence of adopting a full-field technique. It also evident that by analyzing the sequence of thermal images it is also possible to get information about the crack propagation path. From Fig. 4, for example, it can be inferred that the crack propagates along the central median line passing through the two notches starting from left to right. However it should be observed that when a sufficient increment of temperature starts to appear the crack is at about half the width of the specimen, this means that all the above considerations should be considered valid only starting from an advanced stage of the overall fatigue test. In Fig. 5 it is presented the typical behavior recorded on the Ti grade 5 samples; the plot represents the cumulative number of hits, that is to say the number of acoustic waves recorded having an amplitude overpassing the threshold, as a function of the normalized number of cycles. The graphs displays the typical features found elsewhere for this kind of measurements [21]. In particular three different stages can be observed. In the first part of the experiment (stage I), there is a rapid increment of the number of recorded hits which approximately takes 20 % ÷ 30 % of the total lifetime that can be reconnected to crack initiation phenomena and plastic deformations at the tip of the notch [24]. Stage II is characterized by a much lower acoustic activity mainly connected with stable crack propagation. In all the tested sample that came to rupture this second stage takes about 50 % ÷ 60 % of the total life. Finally in the stage III a new rapid increment of the number of hits is observed as a consequence of the onset of the unstable crack propagation. Furthermore observing the 3D histogram graphs Events vs Time vs Position (Fig. 5) it can be inferred that by AE it is also capable to localize position of acoustic events. It appears that most of the events occurs in the region next to the notch and are strictly connected with crack propagation. However, with respect to IR thermography detection, the localization can happen much earlier.

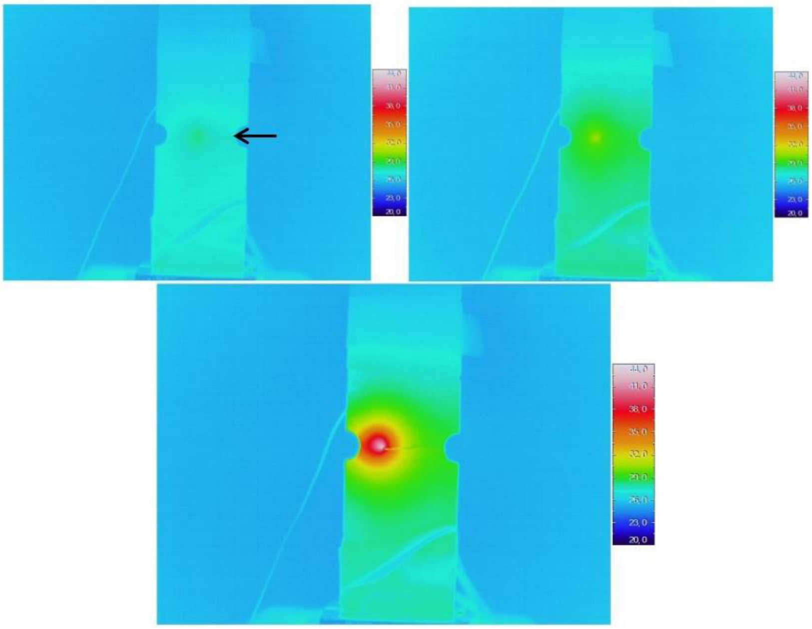

Fig. 4 Sequence of thermographic images indicating the position of the crack tip at different stages of the fatigue test

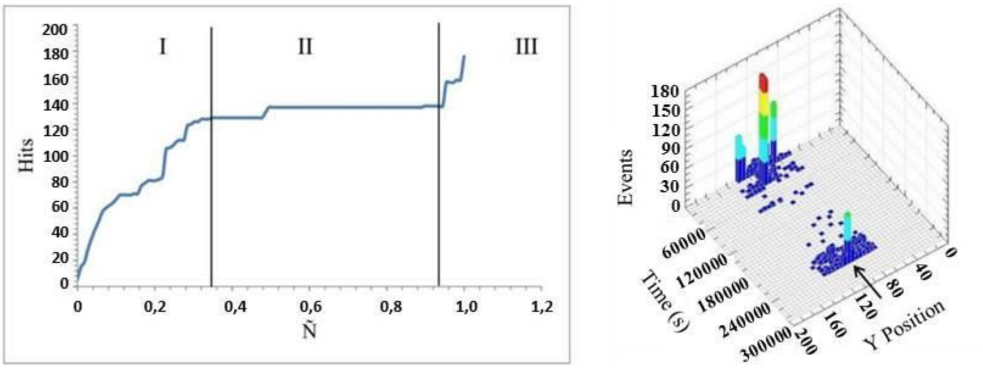

Fig. 5: (Left) Hits vs Normalized number of cycles recorded on one of the tested specimens: (Right) Events vs Time vs Y position graph of the recorded acoustic events.

4. Conclusions

In this paper two different non-destructive techniques were used to monitor fatigue behavior of Ti grade 5 sample subjected to uniaxial fatigue loading. It was observed that IR thermography becomes efficient to localize and to monitor crack propagation only when crack dimension becomes relevant. Only at that point the rise of temperature around the crack tip is high enough to allow detection of crack position and crack path. In that situation however, localization appear to be very precise because the technique provides 2D information with a very good resolution. AE techniques proved to be much more efficient in monitoring crack activity since from the very first moments of the test and allows to distinguish crack initiation stage from stable and unstable crack propagation stage. However in the 1D configuration adopted for the two AE sensors only longitudinal coordinate of the event is measurable. Combination of both the technique appears promising as a powerful non-destructive tool for fatigue monitoring.

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