Combined experimental methods to assess the fatigue limit

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Abstract. Purpose of this paper is to perform an energetic analysis on metal specimens under fatigue testing using the simultaneous application of different non-destructive techniques: thermography (TH), acoustic emission (AE) and digital image correlation (DIC). They assure the better evaluation, being contactless methods, usable in real time and, even if TH and DIC are related to the specimen surface, representative of the inside state of the materials. In particular, the cascade of hits and the acoustic energy were recorded to assess the parameters linked to the fracture of the materials. At the same time, the surface temperature, detected by a thermocamera, and the displacements induced on the specimen, using the DIC on the free zone of the specimens, were recorded. The DIC analysis allows the evaluation of the correct displacement by a pattern realized on the opposite face respect to TH. AE data and hysteresis curves (derived by DIC) were compared with the measures acquired by TH and reveal a reliable correlation between them in terms of fatigue limit.

1. Introduction

Energetic approaches are widely used to preview structure failures, often preceded by different energy emissions in the form of heat, sounds or vibrations. They could be detected during the fatigue life, following the crack nucleation and propagation. In the present study the coupling of different energy methodologies was considered: Thermographic analysis (TH), hysteresis area by Digital Image Correlation (DIC) at high velocity and Acoustic Emission (AE).

Many researchers have performed different methodologies to detect the fatigue parameters using thermography in rapid tests and, consequently many procedures were defined to assess the fatigue and fracture limit, applying single load or a sequence of incremental loading steps [1-19]. These procedures allow assessing the fatigue life [5], the cumulative damage [14], and finally, the fatigue limit under the application of simple static loading also [20-23]. The latter method is based on the limit of the linear thermoelasticity as the starting of the fatigue process [24, 25].

Digital Image Correlation (DIC) is widely used to assess the correct displacements in specimens under static or dynamic loading and can be usefully exploit to define the area of hysteresis, linked to the state of damage of the specimen [23, 26-36].

Acoustic Emission (AE) was proposed as a control methodology, becoming one of the more effective Non-Destructive Techniques in the industrial field. It can be also used to define the fatigue parameters, detecting the hits and their acoustical energetic amount to highlight the fracture propagation [37-40].

Following some studies assessing fatigue parameters by coupling different methodologies [23, 34-40], the aim of the present paper is the comparison about the results found by coupling TH, DIC and AE to define the fatigue parameters and the crack growing in static and dynamic testing. In particular, the
paper describes the evaluation of the fatigue limit using the three methodologies and the comparison among them.

2. Materials and methods
Several tensile and fatigue tests have been performed on dog bone shaped specimens made of S275JR steel with a cross section and a gauge length of 20x6.5 mm, respectively.

2.1. Experimental setup
In order to perform at the same time TH, AE and DIC acquisitions, the specimens were accurately prepared before the tests. In particular, black paint, for the TH, and a random black and white pattern, for the DIC, were applied on the opposite sides of the specimen, respectively. Moreover, the two EA sensors were positioned and fixed symmetrically at the opposite ends of the gage length, with a small layer of grease interposed by the specimen and the sensors themselves, useful to transmit the acoustic emissions. The two piezoelectric sensors, connected to the corresponding preamplifiers, allow localizing the emission source along the axis of the specimen.

For the detection of the AE signals, it was used a AMSY4-MC6 Vallen System, with a central unit equipped with four ASIPP acquisition cards and four channels and an Analog Digital Converter (ADC) sampling frequencies up to 10 MHz and with a resolution of 16 bits by eliminating the lower frequencies. The AE sensor were placed at a distance of 75 mm, symmetrically respect the middle point of the specimen. A Hsu-Nielsen test was carried out for the calibration of the acoustic signal. As a result, a suitable threshold value of about 43 dB (for the static tests) and 50 dB (for the fatigue tests) with a 34 dB gain of the acoustic signal have been set. Rise time, duration, maximum amplitude, energy and number of hits were acquired.

A Flir ThermaCAM X6540 SC thermocamera was used, operating in the infrared field having a spatial resolution of 320x240 pixels, thermal resolution of 20 mK. The thermal images were acquired and processed using the Flir ThermaCAM Researcher Professional 2.10 software.

Both the static tensile tests and the dynamic fatigue tests have been analysed by means of the DIC technique. In the static tests, the images were acquired by a standard Image Source DMK23G445 monochromatic camera. In the dynamic tests, in order to evaluate the hysteresis cycle at different instants of the tests, the images were acquired by a high-speed Phantom V711 rapid camera. The DIC analysis has been performed using the Gom Correlate software.

The tests have been performed by means of an Instron 8501 hydraulic testing machine with a 100 kN load cell both in cyclic loading (under loading control) and in static loading (under displacement control). Fig. 1 shows the experimental setup with the thermal camera on the right, the high-speed camera on the left, and the specimen with the acoustic sensors clamped in the testing machine in the middle.

2.2. Testing procedure
Static tests were run with a test speed of 1 mm/min. During the tests, the acoustic emission parameters and the thermal gradient were recorded. From the acoustic signal it is possible to derive and plot the cascade of hits trend and the cumulative acoustic energy. The cascade of hits ranks in a single event all the “hits” that exceed the threshold value set in a time interval.

As already known, basing on the thermoelastic phenomenon, the fatigue limit can also be estimated from the slope change on the thermoelastic curve [20]. The deviation by the linear thermoelastic behaviour, in fact, highlights the beginning of the thermoplastic phenomenon, strictly linked to the damage process and, then, to the fatigue limit.

Fatigue tests were run with R=−1, frequency of 10 Hz and loading trains of 1000 cycles each, starting from ±10 kN to ±30 kN with steps of ±2 kN to ±5 kN each. The tensile-compressive stress, as a consequence, varied from ±80 MPa to ±240 MPa.
3. Results and discussion
An example of the AE and TH responses as a function of stress are reported in figure 2 for the fatigue loading. The number of hits and the AE energy were processed evaluating their behaviour at the different stress applied (figure 2a), as well as the thermal increments respect to the initial temperature (figure 2b). It is possible to put in evidence as both the methodologies converge to the same value of stress (about 80 MPa).

At the same time, using the displacements obtained by the DIC processing, it was possible to determine the hysteresis curve, thanks to the acquisition by the rapid camera. It was necessary to allow a load frequency high enough to assure an easy acquisition of the thermal variations (proportional to the frequency) and to control local plastic phenomena. An example of the hysteresis curve for a load step is shown in figure 3a. The amount of the mechanical energy (expressed by the hysteresis areas) is shown in figure 3b as a function of the applied stress. Once again, the curve, representing the mechanical plastic energy, converges to the same value of the AE and TH responses, demonstrating that also the measure of the hysteresis areas can be used to assess the fatigue limit. In particular, the values obtained by the
different techniques show a close agreement between AE (80.5±1.1 MPa) and DIC (77.8±2.9 MPa). The fatigue limit assessed by TH provides affine values (90.0±1.2 MPa), even if they tend to be higher.

These results, as a whole, confirm the potential of multi-technique approaches, but also suggest the need to deepen the investigation on the comparison between the three techniques used also for other materials and to compare it with that obtained using other traditional or innovative methodologies.

**Fig. 3.** Example of hysteresis curve detected by DIC (a), and hysteresis area as a function of the stress applied (b).

4. Conclusions

Series of tests were carried out on specimens in S275JR steel, coupling the methodologies of acoustic emission, digital image correlation and thermography, in order to verify the possibility to detect the fatigue limit by the comparison of the three forms of energy: thermal, mechanical and acoustic. The tests were performed under static tensile loading and under cyclic loading at R=−1.

The results obtained show that the acoustic emission is able to define the fatigue limit, either in terms of cascade hits or in terms of released energy, as well as the thermographic analysis, already tested by many authors. By the DIC displacements the hysteresis areas were calculated and, once again, the curve of the plastic mechanical energy converges to the same fatigue limit. Then, the acoustic emission parameters as well as the hysteresis areas can be used to define the fatigue limit using a methodology similar to that applied by thermography. The approach needs to be better study in deep to verify if the energetic amount detected by acoustic emission could be better linked to other fatigue parameters and, in this case, translate the results acquired by thermography to the other methodologies.

The results obtained show as all the methods converge to the same fatigue limit, demonstrating that all the forms of detected plastic energy (thermal, acoustic and mechanical) can be used (separately or combined) to determine the fatigue behaviour.

Following these results, the authors intend to prosecute the analysis on a larger series of specimens to better investigate the correlation between the energy detected by the different methodologies, in order to formulate a reliable procedure based on a combined data analysis able to predict the fatigue parameters.

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