Fatigue analysis by acoustic emission and thermographic techniques

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Abstract

Aim of this paper is to evaluate how two non-destructive testing techniques may be integrated in a methodology to analyze the fatigue on materials. The compared techniques are the acoustic emission and the thermography. Both the techniques are able to reveal the strain energy even if was produced by strictly localized phenomena, as in the fatigue process. Moreover, both the techniques use the energy directly produced by the stressed body without any external source, differently from other NDT (US, X-Rays ...). The experimental tests were carried out on flat steel specimens either under static loading or under sequences of increasing cyclic loading (R=0). The results allow to define the fatigue limit either by the thermography or by the acoustic emission. The present work is a first approach performed by the authors to compare and integrate the results obtained by experimental tests where the two methods were simultaneously applied.

1. Introduction

Structure failure is often preceded by different kind of warnings: sounds and vibrations are often a precursor signal indicating the approaching collapse. Many materials or metal components before breaking emit sounds warning of breakdown. Since the first studies performed in the forties and fifties [1, 2], the researches allowed to assure the correspondence among the crack propagation and the number, intensity and energy of acoustic events. On these bases, the Acoustic Emission (AE) was proposed as a control methodologies and, with the progress of

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technology, either in terms of detectors or in terms of data processing, AE became one of the more effective Non-Destructive Techniques, primarily in the industrial field. One of the main advantages of the AE technique is the possibility to operate directly on the mechanical component/system while working and, using an appropriate number of detectors, to identify the crack position and the degree of fatigue reached by the system itself [3-7].

At the same time, other techniques allow monitoring the crack nucleation and propagation long before the rupture occurs. Many authors found that, under fatigue loading, thermal increments can be measured on the specimen surface, as higher as the load exceeds the fatigue limit, highlighting how a phase of micro yielding started [8-22]. Also in this case, the thermographic (TH) methodology can be applied on specimens and components while working and, moreover, it offers the advantages of a remote sensing technique. More than thirty years of worldwide researches defined that, under cyclic loading, the temperature increases, for many metals and non-metals, following three subsequent phases: a first increment in the first phase (normally a small fraction of the lifetime) until reaching the thermal equilibrium and a stabilization temperature (second phase, for most of the entire life) and, finally, a quick thermal increment just before failure. Several procedures were defined in order to forecast the most important parameters of the fatigue and fracture processes: fatigue limit, fatigue life, crack nucleation and propagation. Among the above-mentioned procedures, studies were carried forward on the fatigue limit by different applied loads and by incremental loading steps, the fatigue life determination, the cumulative damage [23], the application to mechanical components while working and as control technique in production [24] and, finally, the possibility to define the fatigue limit under the application of static loading [25-29]. Particularly, the latter method considers the limit of the perfectly linear thermoelasticity as the crack starting and, then, the beginning of the fracture process.

Considering the great affinity between the two NDT techniques, even if related to different parameters, acoustic-energetic for AE, thermal-energetic for TH, the authors tried to couple both in dynamic testing [30] in order to verify the correspondence between them. Following the first experimental tests and some recent studies demonstrating the possibility of detecting fatigue parameters by the coupling of the two techniques [31-33], aim of the present paper is a first approach to the definition of the setup and procedure to acquire the more reliable information about the fatigue parameters and the crack growing.

2. Description of the investigation

As previously defined, the aim of the study was the simultaneous application of the two NDTs to specimens and the comparison among the data detected. In order to analyze the correspondence between the two methodologies, two sets of trials were carried out, the first one under static loading, the second one under cyclic loading. The tests were conducted on steel specimens in two different campaigns.

2.1. Experimental setup

The tests were conducted on specimens in C40 carbon steel and AISI 304 stainless steel shaped for static tests. The latter, particularly, was considered to take advantage of the high thermal response of this kind of material. All the specimen dimensions are showed in Table 1.

| Material  | Overall length (mm) | Thickness (mm) | Distance between shoulders (mm) | Width of grip section (mm) | Width of reduced section (mm) | Fillet radius (mm) |
|-----------|---------------------|----------------|---------------------------------|---------------------------|-------------------------------|-------------------|
| AISI 304  | 210                 | 5.0            | 80                              | 20                        | 12.5                          | 40                |
| C40       | 0                   | 5.7            | 80                              | 20                        | 12.8                          | 40                |

The static tests were conducted using a Zwick-Roell Z100 testing machine with a 100 kN load cell under displacement control. The dynamic tests were carried out by an Instron 8501 testing machine with a 100 kN load cell always under displacement control.

The Acoustic Emission data were acquired by the AMSY4-MC6 Vallen system equipped with two ASIPP acquisition boards and relative pre-amplifiers (Figure 1). The signals detected by the sensors (only two channels
were used) were processed by the Vallen AE-Suite software (Figure 2) and, after, imported and processed by Microsoft Excel.

Two sensors were applied on each specimens near the clamps, on the reduced section borders, using MoS$_2$ silicon grease to assure the acoustic coupling and fixed by a thin tape strip (Figure 2), narrow enough to permit the almost complete thermal vision of the reduced section. Score-Atlanta (Dunegan/DECI) SE375-M standard AE sensor for general purpose testing, 375 kHz peak sensitivity, were used.

The thermal images were acquired using a FLIR ThermaCAM SC3000 (Figure 4). The thermal camera has the sensors cooled by a Stirling device and assures a thermal resolution up to 20 mK and a spatial resolution up to 320x240 pixels. A sequence of thermal images for different cyclic loading pulse trains is shown in Figure 3.

2.2. Experimental procedure

Either for the static tests or for the cyclic ones, the specimens were sprayed with black matt paint, to avoid all the reflections from the specimen, on the side detected by the thermal camera. The AE sensors were set on the opposite side. In order to minimize the thermal disturbance from the environment, the thermal camera, once mounted on a suitable tripod, was covered by a thermostatic box. The thermal maps were acquired along the whole test on the entire specimen surface. Moreover, three spots were pointed on the surface, in upper, medial and lower position, to acquire directly the behavior of the thermal variations.

The first series of tests was carried out under static loading in displacement control with 1 mm/min cross-head speed. The second series was carried out under cyclic loading ($R=0$). The loading pulse trains were applied at 10 Hz for 500 cycles, with increasing steps; the stresses induced are represented in Figures 14 to 17. Consecutive tests were performed on the specimens in order to verify the cumulative damage.

The values of threshold and gain were defined, for each test, defining the attenuation by the Hsu pencil lead break test broken on the specimen surface. Once set the main parameters, the following AE data were acquired: number of hits, amplitude, energy, cascade hits, source position.

3. Analysis of results

3.1. Static tests

The number of hits and the related energy for one of the static tests on AISI 304 were shown, as an example, in Figures 5 and 6 together with the applied stress. Both the AE parameters increase almost linearly in the first phase, following the load increasing and reduce the slope in the plastic zone. The AE parameters increase roughly following the stress behavior and show clearly the passage from elastic to plastic zone. On the contrary, no particular information can be achieved in static analysis at this stage by AE in the elastic zone.

The elastic and plastic zones can be also defined by the thermal response in Figure 7 for AISI 304, showing the thermal behavior of three different spots on the specimen. On the base of the theory of thermoelasticity, the yield point can be defined as the inversion of the thermoelastic behavior, then the minimum value reached by the thermal variation (at about 145 s), corresponding to a stress of about 300 MPa.

An example of the stress curve for C40, together with the thermal response in three spots on the specimen, adequately filtered to highlight the midline, is shown in Figures 8 and 9. The thermoelastic yield appears at about 180 s, corresponding to a stress of about 300 MPa.

By the thermographic response, it is also possible to define the limit of perfect thermoelasticity, corresponding to the micro-cracks nucleation and strictly correlated to the fatigue limit [25-29]. It can be identified in the slope change after the first linear, totally elastic, decrease, when the deviation from the linearity testifies that the plastic process begun, limiting the decrease and initiating the production of plastic heat.
The point of the slope variation is reached in about 90 s for AISI 304 (Figure 7), corresponding to a stress of 180 MPa. Similarly, the thermal variation on C40 defines a thermoelastic limit at about 90 s (Figure 9), corresponding to a stress of 130 MPa.
3.2. Cyclic tests

The comparison among the AE results and the thermographic response are reported in terms of cascade hits as a function of the time either for a C40 specimen or for the AISI304 one. This parameter considers essentially the relative amount of sequences exceeding the defined threshold, starting from the loading application. Figures 10 and 11, as an example, put in evidence the close correspondence with the thermal increments. The temperature variations have a gradient increasing with the applied load, as well as the number of hits. A similar increasing behaviour, but with a lower correlation, can be considered in terms of released energy (Figures 12 and 13).

A better correspondence among TH and AE results can be expressed in terms of applied stress instead of time and, then, in terms of strain, being the performed tests under displacement control. By applying the thermographic methodology used for the determination of the fatigue limit and now widely tested by many authors, Figures 14 and 15, derived by the previous ones, demonstrate how both the AE and TH converge to the same limit, corresponding to the intersect with the stress axis or the first cyclic load producing thermal increments due to the plastic energy released. In this case, the curves of the release energy also converge to the same value (Figures 16 and 17), pointing out the possibility to define the fatigue limit also by the analysis of the AE energy. The convergence of both the TH and AE curves allows considering the AE methodology able to define the fatigue limit, either in terms of hits or in terms of energy, as well as the thermography in terms of initial gradient or in terms of stabilization temperature.
Fig. 10. Temperature variation compared with AE cascade hits for a C40 specimen.

Fig. 11. Temperature variation compared with AE cascade hits for an AISI 304 specimen.

Fig. 12. Temperature variation compared with AE energy (in energy units x 1000) for a C40 specimen.

Fig. 13. Temperature variation compared with AE energy (in energy units x 1000) for an AISI 304 specimen.

Fig. 14. Temperature variation compared with AE cascade hits for a C40 specimen.

Fig. 15. Temperature variation compared with AE cascade hits for an AISI 304 specimen.
Finally, it could be interesting to observe that the fatigue limit for the C40 specimens, detected by the AE and TH techniques together (about 130 MPa), corresponds to that defined by the static analysis in Figure 9. The same result is achieved for AISI 304, with a fatigue limit defined by both the techniques, of about 180 MPa. It confirms once more that the fatigue limit can be detected by the simplest tensile static test coupled with the thermographic analysis and encourages the authors to prosecute the research in order to correlate more deeply the TH and AE responses with the fatigue parameters.

4. Conclusions

On the basis of previous studies, a first series of tests was carried out on specimens in steel, coupling the two methodologies of acoustic emission and thermography, in order to verify the possibility to detect the fatigue parameters and to compare the results obtained. The tests were performed either under static or cyclic loading, considering that, also in the static field it is possible to define, by thermography, the limit of the linear thermoelastic zone, corresponding to the first appearance of the local plastic phenomenon.

The results acquired by acoustic emission in static field put well in evidence the passage between the elastic and plastic zone. The amount of hits and the energy increases with the applied load, as was to be expected, but the acoustic emission data don’t evince particular behavior until the yield. At the present stage of research they don’t give any useful information about the fatigue parameters as well as the thermographic data.

On the contrary, the results obtained under cyclic testing show that the acoustic emission response 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. The first approach needs to be better analysed in order to verify if the energetic amount detected by acoustic emission could be better linked to cumulative thermal parameters. The first acoustic emission results, however, can be used to define the fatigue limit with a methodology similar to that applied by thermography.

The fatigue limit found by the cyclic tests, obtained by the two different techniques, moreover, confirms that found as thermoelastic limit by the static ones, as predicted in previous papers.

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

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