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Fatigue limit assessment by energetic analyses in static and cyclic tensile tests

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Abstract

Inside a research program agreed with the AIAS-MEAS Energy Methods Group, this preliminary study starts defining the fatigue parameters of a commercial steel in static and cyclic loading conditions. The final purpose of the research is to define the fatigue limits in different loading conditions using different energetic methodologies and comparing them with those derived by several tests performed by the other researchers of the Group. This first step was carried out using the thermographic methods already proposed in literature, determining the values of the fatigue limit for R=0. At the same time, the thermal response in static tests were derived in order to correlate the limit of the totally thermoelastic behavior, corresponding with the phase of the crack nucleation, with the fatigue limit.

Keywords: Fatigue limit, static and cyclic testing, thermographic method.

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1. Introduction

A research program was defined inside the AIAS-MEAS (Energy Methods for the Experimental Analysis) Group, involving several Italian Universities, with the aim of applying different methodologies to define the fatigue limit and other fatigue parameters on steels. On this basis, the first step of the Catania Unit was to define the fatigue limit by the thermographic method and beginning to correlate it with the thermal response in static tests. The whole program

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of Catania Unit provides for the application of different non-destructive techniques and the comparison of the results obtained in terms of fatigue limit. Many researchers have carried out different methodologies to detect the fatigue limit using an energetic approach, mainly InfraRed Thermography (IRT), in rapid tests (Bodner et al. 1983, Luong 1988, Kaleta et al. 1990, La Rosa and Risitano 2000, Klingbeil 2003, Boulanger et al. 2004, Plekhov et al. 2007, Maquin and Pierron 2009, Naderi et al. 2010, Crupi et al. 2011, Risitano et al. 2015, Fargione et al. 2017) or the whole S-N curve (Fargione et al. 2002).

In the last years, the use of the Digital Image Correlation (DIC) was largely used to evaluate the correct displacements in specimens under static or dynamic loading, also in order to define the area of hysteresis, representing the loss of energy and linked to the state of damage of the specimen (Wattrisse et al. 2001, Kanchanomai et al. 2002, Sánchez-Arévalo and Pulos 2008, Hunady et al. 2012, Roy et al. 2013, Li et al. 2016, La Rosa et al. 2016, 2017, 2018).

Coupled with IRT, other energetic methods were also used to define the fatigue limit, involving either the thermal or the acoustical energy, detecting the hits and their energetic amount linked to the fracture propagation (Naderi et al. 2012, Kordatos et al. 2012, 2013, La Rosa et al. 2014, Giudice et al. 2019). Finally, new considerations were performed on the thermal behavior in static analysis. Beyond the perfectly elastic limit of the well-known thermoelastic effect, correlating in a linear way the thermal variation and the applied stress, the thermal curve changes slope due the first local plasticization, before strongly rising in correspondence of the yield stress (Caglioti 1982, Melvin et al. 1990). Some researchers consider the point in which the curve deviate from the linearity as the crack nucleation point, correlate to the fatigue process (Clienti et al. 2010, La Rosa and Risitano 2014, Risitano et al. 2011, 2014, 2015, Risitano and Risitano 2013).

In the present study, in particular, the following energy methodologies will be used: Thermographic analysis (TA) and Hysteresis by Digital Image Correlation (DIC) at high velocity. The coupling between Acoustic Emission (AE) and Thermography will be object of a further investigation.

2. Description of the investigation

The AIAS-MEAS Group agreed to perform all the tests on the same C45 commercial steel and the Research Unit of Padua, in order to avoid any differences among the specimens, provided all the other units with the same flat specimens, shaped following the ASTM E606 standards.

2.1. Experimental setup

Static and cyclic tests were carried out by an Instron 8501 testing machine with a 100 kN load cell under loading control. Thermal images were acquired by FLIR ThermaCAM X6540SC cooled by a Stirling device, with a thermal resolution <20 mK, and a spatial resolution 320x240 pixels. The images were processed by the FLIR ThermaCam Researcher Professional software. Fig. 1 shows the scheme used to acquire thermal and DIC images. Fig. 2 shows the setup used for the static tests (without the DIC camera).

Drawing the hysteresis ellipse by the DIC images needs a large number of points (20-30), then a low frequency of the load application. On the contrary, the thermal variation amount is proportional to the load frequency. Using the standard video cameras (from 30 to 60 fps) the maximum loading frequency can be 1-2 Hz. Then a high frame rate camera needs to assure the adequate number of frames per cycle to be processed to define a reliable hysteresis cycle. A Phantom v711 rapid camera with maximum frame rate of 10^6 fps was used. In order to have at least 20 images per cycle and a good spatial resolution (1280x800 pixel), the acquisition was programmed at 200 fps. The images were recorded for the time of 0.2 s at the beginning and at the end of each loading step, to verify the stability of the hysteresis along each step; in this way, there were images enough to calculate the strain for 2 consecutive cycles. Fig. 3 shows the strain derived by the DIC images, calculated by the software MatchID.

2.2. Test procedure

The test procedure includes two different paths related to the characterization of C45 steel specimens in a static or cyclical field. In this first phase the cyclic load was applied with load ratio $R = 0$.

Three specimens with static tensile loads were tested, determining the yield stress, necking and breaking values. In the same test, the thermal variations (Fig. 4) were detected and were associated with the corresponding stress level, evaluating the yield stress according to the energy indications (Caglioti 1982, Melvin et al. 1990).

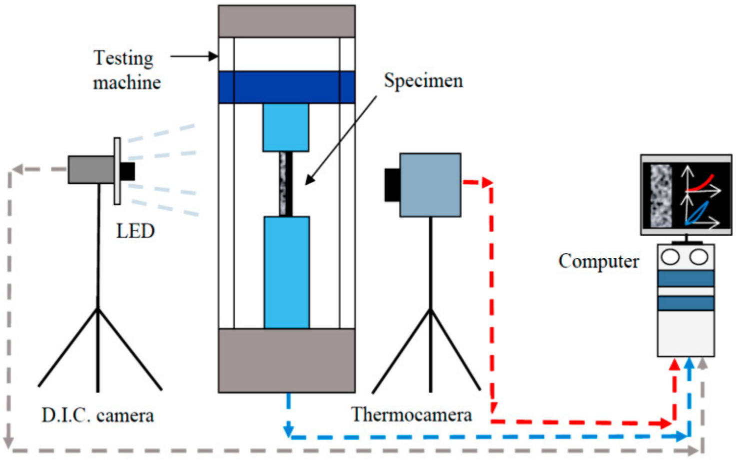

Fig. 1. Scheme of the setup used for the TA/DIC cyclic tests.

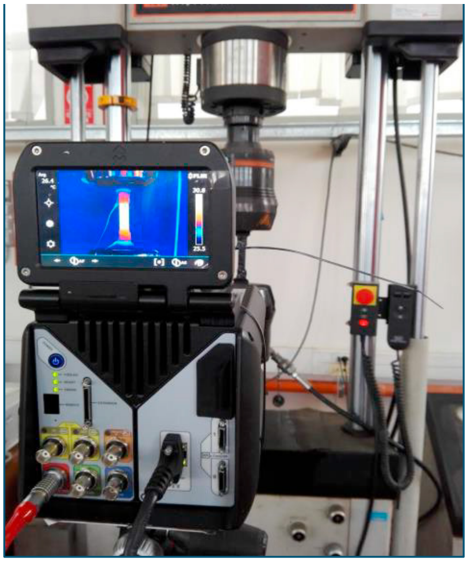

Fig. 2. Setup used for the TA static tests.

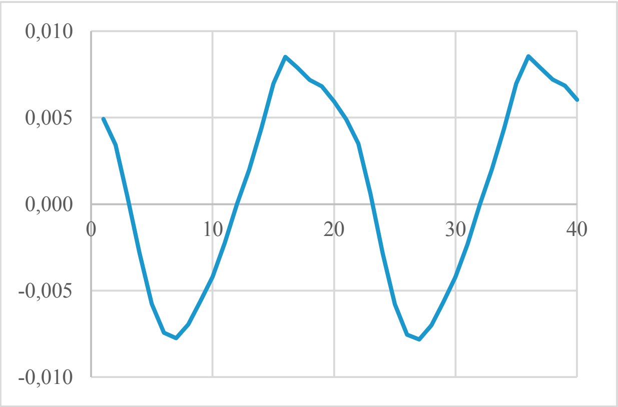

Fig. 3. Strain derived by the rapid camera.

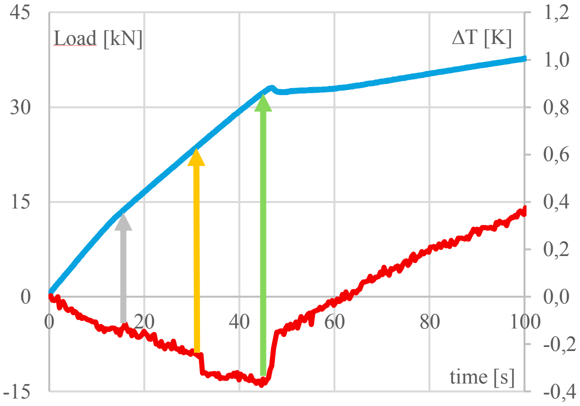

Fig. 4. Stress-strain curve and thermal response in static test.

Three specimens with increasing cyclic loading were also tested with incremental steps, and also along these tests the thermal variations were detected (Fig. 5). The frequency of application of the load was 10 Hz, to ensure a sufficiently significant thermal variation. The acquisition frequency of thermal images was 60 Hz, compatible with that of the load to have a sufficient number of images per cycle.

3. Analysis of results

The first reliable results can be correlated to the definition of the yield stress and to the fatigue limit at R=0, both by the thermographic method.

In relation to the yield stress, Fig. 4 shows the diagrams of the applied load together with that of the maximum thermal variation, detected at the central point. The positive thermal jump is clearly visible in correspondence with the minimum of the thermal curve (green arrow). This corresponds to the yield point in the load-deformation curve. The value derived is 460 MPa, very similar to those found by the other Research Units. In the same figure it is possible to highlight two other discontinuities from the thermoelastic behavior (gray and orange arrows), at the values of about 190 MPa and 320 MPa respectively. The first one is less noticeable, not found in all tests performed, and deserves a deeper investigation and further measures. Instead, the latter (orange arrow) shows an evident and quick variation and a value not far to those found by the other Research Units (295-308 MPa) for R=-1, corresponding to the lower value for the fatigue limit. Even if it is only a partial result, this analysis encourages to prosecute the studies for detecting the point of the crack initiation.

Fig. 5 shows the thermal increments detected during one of the cyclic tests with R = 0 with incremental load steps. The figure also shows how the random interruption of the test (due to a temporary detachment of the testing machine) does not affect the stabilization temperature reached at each train of load pulses. This random interruption, on the other hand, can be used to evaluate the behavior of thermal decay, which is the basis of other test methods for the evaluation of the fatigue limit (Meneghetti 2007, Meneghetti et al. 2013, 2019).

The value detected by the thermographic analysis for the fatigue limit at R=0, on the contrary, can be considered reliable for all the tests performed at 400-410 MPa (Fig. 6). The result is in line with the results deduced from the other Research Units for similar values of load ratio. Also in this case the result obtained confirmed the reliability of the methodology, indeed already confirmed by numerous researchers.

More deep considerations will be carried out at the end of the whole research program, when the energetic test will be compared with the traditional ones (for example, stair case method).

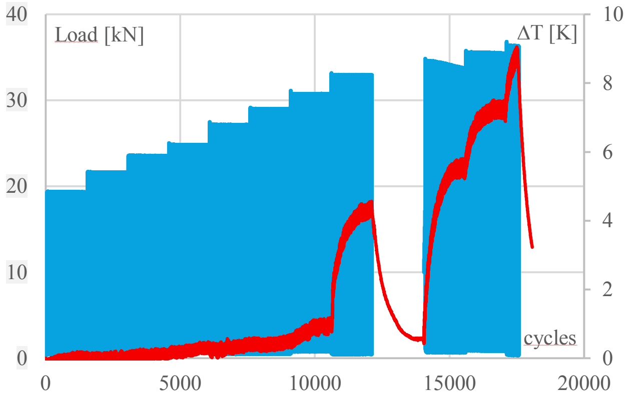

Fig. 5. Load (blue line) and thermal (red line) response in the increasing step test (R=0).

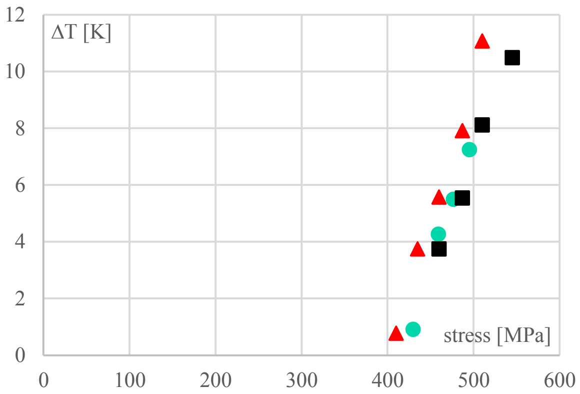

Fig. 6. Fatigue limit detected by TA (R=0).

4. Conclusions

A research program has been defined among researchers of several Italian universities (AIAS-MEAS Group) for the application of rapid energy methods for the evaluation of the fatigue parameters of steels using different methodologies. It was agreed to carry out tests on a commercial steel (C45) commonly used in metallic carpentry.

In this first phase, the Catania Research Unit focused on static and cyclic tests with load ratio R = 0. The results obtained confirm the validity of the thermal methods in static field for the determination of the yield stress and highlight different slopes of the thermal profile also in the macroscopically elastic field but not easily identifiable as fatigue parameters.

On the contrary, the results found for the cyclic loading at R=0 show a reliable value of the fatigue limit derived by the thermographic analysis using the incremental loading steps method and are in good agreement with those derived by different methodologies by other researchers of the AIAS-MEAS **G**roup.

Next steps will include:

- the definition of the fatigue limit for R=-1,
- the definition of the fatigue limit by the static method and the comparison with the fatigue limit at R=0 and R=-1,
- the hysteresis analysis by DIC and the comparison between thermal and mechanical energy,

- the comparison between thermographic analysis and acoustic emission, in order to verify the compatibility of the results obtained in terms of fatigue limit.

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