Thermographic-DIC approach in fatigue behaviour analysis

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Abstract. A research program was carried out by a group of researchers of nine Italian universities in order to define the fatigue parameters of a commercial steel. The purpose is to define the fatigue limits in different loading conditions and comparing the results obtained by tests performed using different energetic methodologies. In this paper the thermographic method already proposed in literature was performed, determining the Haigh and Goodman-Smith limit curves. At the same time, the thermal response in static tests were derived in order to correlate the limit of the totally thermoelastic behaviour.

1. Introduction
During a meeting of the AIAS-MEAS (Energy Methods for the Experimental Analysis) Group, a research program was arranged in order to define the fatigue parameters of the same commercial steel applying different methodologies. All the specimens tested in several different universities were provided from the colleagues of University of Padua, to assure the homogeneity of the material. Aim of the Catania Unit was defining the fatigue limit and, later, the entire fatigue curve, using the thermographic method and correlating it with the thermal response in static tests.

Since the eighties, many researchers have performed several methodologies to detect the fatigue limit by an energetic approach. Most of them used InfraRed Thermography (IRT) for rapid tests [1-12], also extended to the whole S-N curve construction [13]. To the basic approach, which involves the measurement and analysis of the surface temperature, other “local energy” approaches have been added over time, based on the analysis of the intrinsic heat sources related to thermomechanical phenomena within the material, both reversible (thermoelastic sources) and irreversible (dissipative phenomena) [6, 14-17].

Since the last decade, Digital Image Correlation (DIC) was largely used mainly to evaluate the correct displacements in specimens under loading. The correct information about the forces and displacements allows also to define the area of hysteresis, representing the loss of energy per cycle, linked to the state of damage of the specimen [18-27].

Other methods based on the energetic analysis were also used to define the fatigue limit, particularly the acoustical energy, detecting the hits and their energetic amount, methodology largely used in fracture mechanics [28-31].

Finally, some considerations has to be carried out about the thermal behaviour in static analysis. Materials under static loading initially present a perfectly elastic behaviour (thermoelastic effect), linearly correlating the thermal variation to the applied stress. Then, the thermal curve changes slope due the first local plasticization, before strongly rising at the yield stress [32-33]. The point where the
curve deviate from the linearity could be considered as the crack nucleation point, to be correlate to the fatigue process [34-37].

In the present study, Thermographic Analysis (TA) and Digital Image Correlation (DIC) at high velocity were applied and the fatigue limit was defined at different loading ratios.

2. Description of the investigation

As previously described [38], all the tests were performed on the same C45 commercial steel, shaped following the ASTM E606 standards, in order to avoid any differences among the specimens tested by the different laboratories using different methods.

2.1. Experimental setup

Tests were performed by an Instron 8501 testing machine with a 100 kN load cell under loading control either under static or cyclic loading.

Thermal maps and DIC images were acquired contemporaneously on the opposite sites of the flat specimen. Thermal maps were acquired using a cooled FLIR ThermaCAM X6540SC, with a <20 mK thermal sensitivity and a 320x240 spatial resolution. The images were processed by the FLIR ThermaCam Researcher Professional software. In the thermal maps a dummy specimen (unloaded) was used to compensate the environmental effects, using a differential technique similar to that used for strain gauges. Figure 1 shows the scheme used to acquire thermal and DIC images.

The DIC images need a large number of points (20-30) in order to reconstruct the hysteresis curve, needing of a low load frequency. On the contrary, the thermal variation amount is proportional to the load frequency. Using a standard video camera (30 to 60 fps) the maximum loading frequency can be 1 to 2 Hz. Then, 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 400 fps. The images were recorded for the time of 0.2 s at the beginning, at the mean time and at the end of each loading step, to verify the stability of the hysteresis along each step. DIC images were processed by the software GOM Correlate.
2.2. Test procedure
Following the results obtained for the static tests and the cyclic test with load ratio \( R=0 \), presented in a previous work, the test procedure includes the characterization of C45 steel specimens under symmetrical cyclical loading with load ratio \( R = -1 \).

Five specimens were tested with cyclic incremental pulse train of 2000 cycles each, until reaching the stabilization temperature. The stabilization temperature was not clearly reached for all the specimens, so in doubtful cases the fatigue limit was determined with the initial thermal gradient method. Figure 2 shows the sequence of applied loads and the temperature increments.

[Figure 2. Sequence of loads and temperature increments.]

The hysteresis area were calculated using the data derived by the testing machine. The DIC analysis showed displacements with the same behaviour but values roughly half respect to the machine data. Figure 3 shows the displacements as a function of the time before filtering for the three measurement points under about 23 kN loading (\( \sigma \approx 320 \) MPa).

[Figure 3. DIC strains vs. time.]
3. Analysis of results

Figure 4 shows the areas for different applied loads at the mean time of each train pulse for loads varying from 22 kN to 28 kN detected from the testing machine data. Aim of this analysis is to compare also quantitatively the energy detected by the thermal acquisition $Q = \rho \, c_p \, \Delta T$ with that calculated by the hysteresis areas. As demonstrated in a previous paper [27], not only the behavior of the curves but also the quantitative values of the energies well agree. Considering the large differences (about twice) between the machine and the DIC displacements, it is possible only using the correct strain derived by local methods as DIC or extensometers. At this stage, a qualitative analysis only was performed.

The hysteresis areas increase with the applied load and show a noticeable ratcheting effect, certainly dependent on the increase in plastic energy accumulated in previous cycles. This phenomenon is evident also during the single train at constant load (Figure 6), showing the damage increasing correlated to the temperature variations of the phase I of the temperature trend (linear thermal increase before stabilization).

![Figure 4. Hysteresis cycles for the different steps by the testing machine.](image)

![Figure 5. Hysteresis at the same step: beginning, mid point and end of the pulse train.](image)
The fatigue limit was derived in two ways: for the tests where the specimens reached the stabilization temperature (phase II), the method of the temperature increments was used, considering the intersect of the regression line with the almost nil zone. For the other, where the phase II was not completely reached, the method of the initial gradient was considered (Figure 6). In both cases, the fatigue limit (yellow arrow) is practically the same.

![Graph](image)

**Figure 6.** Evaluation of the fatigue limit at $R=-1$ by the stabilization temperature (left) or by the thermal gradient (right).

The results are in agreement with those obtained by other rapid energy methods by other researchers of the AIAS-MEAS Group [39].

4. **Conclusions**

Following the research program defined inside the AIAS-MEAS Group for the application of rapid energy methods for the evaluation of the fatigue parameters of steels using different methodologies, other tests were performed. The tests were carried out again on the same commercial steel (C45). In this second phase, the Catania Research Unit focused on cyclic tests with load ratio $R = -1$.

The results obtained confirm the validity of the thermal methods to define the fatigue limit, showing a reliable value of the fatigue limit derived by the thermographic analysis using the incremental loading steps method.

The comparison with the results obtained by different methodologies by other researchers of the AIAS-MEAS Group shows a good agreement.

The DIC analysis performed on three different areas of the specimens confirms a first correspondence with the machine data but values of the strain roughly half. The hysteresis areas grow with the applied loads and show an evident ratcheting phenomenon.

Next steps of the research will include a deeper hysteresis analysis by DIC and the comparison between thermal and mechanical energy.

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