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Mechanical and Dissipative Parameters in Fatigue of Steels

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Abstract: In this paper the effect of high cycle fatigue damaging on a commercial steel is investigated by means of experimental measurement of mechanical and dissipative parameters variation during fatigue testing. Experimental procedures for HCF damage incrementing on specimens and for parameter measurement have been defined. A statistical analysis of the significance of the results have been applied to select the parameters which best represent the damage progression on the specimen.

Keywords: HCF, fatigue damage.

1 Introduction

Mechanical behavior of materials regarding high cycle fatigue, even if widely investigated in literature, may still present some interesting aspects from the point of view of damage at a microscopic scale. Some analytical and empirical models have been developed during the last decades to describe both endurance and damage mechanism during the life of materials or components.

In particular, on the basis of three different fatigue domains, which can easily be described by a Wöhler's curve, it may be established a multiscale approach in order to create a link between the macroscopic damage of a structure submitted to cyclic loading and the corresponding irreversible mechanisms at the grain scale related to the variation of dissipative parameters.

The first case, presenting an elastic shakedown theory [1] at all physical scales, can be easily associated to infinite lifetimes and unlimited endurance. The second case, corresponding to a localized cyclic plastic behavior in some well oriented grains, conducts to High Cycle Fatigue (HCF) and a limited endurance. Finally, the last case, conducts to Low Cycle Fatigue (LCF) phenomenon.

Not only in the finite lifetime domains, but also in the case of unlimited endurance, the damage phenomenon may be observed and analytically modeled [2]. However,

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the experimental validation of these models may cause some difficulties due to the stochastic nature of mechanisms at the grains scale [2], [3].

Thermography, involving surface temperature monitoring of materials and components, and others experimental techniques as microscopy, modal analysis, ..., are well suitable to the analysis of the fatigue damage progress. Measured parameters may be classified in two categories: mechanical, as Young modulus and natural frequency, and dissipative, as hysteresis loop area, modal damping and subtended area of the thermal profile.

As a first meaningful example of this, during the Fifties several studies were conducted about the possibility of a correlation between fatigue damage and internal damping variation, focusing above all on metals.

Some original experimental techniques and mathematical models were proposed (see a wide panorama in [3]), based on hysteresis loop measure and analysis. Professor Lazan's classical work consisted in the measurement of both damping energy and dynamic modulus of elasticity (considerable a physical quantity related to the elastic modulus value), respectively the hysteresis loop area and slope values, thanks to an experimental equipment specifically designed. Results proved a damping variation during the tests ([3], [4]), consisting in an increase due to a bigger tendency of the material to dissipate energy under heat form, and a decrease for the dynamic modulus of elasticity, and moreover emphasized the influence of the stress history on the material behavior. In particular, a threshold stress value below the which internal damping remains constant, called stress sensitivity limit, has been identified.

More recently, several remarks on internal damping have been proposed in [2], where, on the basis of a huge number of experimental studies, prevalently conducted in Soviet Union from the Sixties to the Eighties, it has been assumed as microplasticizations activation indicator [5].

In the last two decades, at least two research groups have continued their experimental activity on damping variation during fatigue testing. In [6], after having modified the Amsler Vibrophore internal damping measurement methodology, a theoretical relationship between thermal increase in fatigued specimens and internal damping variation is found and experimentally validated. In particular, it is observed that internal damping augmentation is relevant just below the yield stress.

In [7], modal analysis experimental tests were conducted on metals, elaborating both internal damping and resonance frequency results on metallic beams. The base of the modal analysis technique to assess internal damping is described in [8], where, by the way, it is applied on high damping alloys characterization and not on fatigue behavior study.

It has to be emphasized that, in general, in these papers the material behavior is mainly justified referring to dislocation motions and microplasticizations activation than microcracks initiation and/or propagation. If modal techniques are utilized to measure internal damping values, a natural consequence of that is also to investigate a related mechanical parameter, the natural frequency of the specimen.

A remarkable number of papers ([9], [10], [11], [12]) has been written on this subject, at least from the Sixties, until today. In general, they are focused on simple components, as concrete or steel rectangular beams, having dimensions higher than the usual fatigue specimens. It has to be emphasized that, in general, the aim of these works is not fatigue damage characterization, but the discussion of resonance frequency measurements as a non destructive technique to monitor cracks in civil structures, as bridges, as an example.

A second remarkable example of mechanical parameter sensitive to damage comes from the Young modulus of the material, even if often related to the threshold of a crack growth [13] or to plastic strains [14].

Finally, the subtended area by the thermal profile and the area of the hysteresis loop have been considered as dissipative parameters. In particular experimental data related to the thermal increment on a fatigued specimen surface may be very helpful in energy dissipation assessing, together with the hysteresis loop area.

Object of the present work is an experimental analysis about the variation of physical parameters, dissipative and mechanical, in order to monitor the fatigue damage in steels. The proposed methodology involves a hybrid technique. In particular some fatigue tests on steel specimens, organized in repeated block of cycles characterized by the same load and test frequency values, has been performed. Damage parameters have been measured at the beginning of the test.

Then, damage parameters have been monitored successively or simply during each fatigue block (hysteresis loop area, Young modulus, subtended area of the thermal profile) or at the end of each block (modal damping and natural frequency). The final aim of this research activity is to evaluate if the above quoted physical parameters are useful to represent the fatigue damage in steels and also easy to be monitored. Fatigue tests were performed on two kind of commercial steels, C45 and C40, using different testing frequencies and considering different stress levels (below, near and above fatigue limit) until $2 \cdot 10^6$ cycles or until fracture occurs. All tests are carried on following the experimental procedure described in [15] and [16].

2 Materials and methods

Materials used for the experimental tests are two commercial carbon steels, C45 and C40.

Fatigue tests have been performed by means of an Instron 8801 Servohydraulic machine (load cell 100 kN; testing frequency: 10 or 30 Hz; load ratio R = 0,1). According to [15] and [16], specimen geometry [15] has been designed according to fatigue [17] and modal analysis test execution requirements (uncoupled flexural modes in two perpendicular planes).

Fatigue tests have been organized in repeated block of cycles characterized by the same load and test frequency values; during the damage procedure, both loading blocks with the same stress level and with continuously increasing levels (starting from values below the fatigue limit, until the yield stress) have been employed.

Table 1 shows the test conditions for all specimens: more in detail, the first column reports both material and identification specimen number, the second column the test frequency, the third the maximum stress value σ_{max}, the fourth the increment value for the stress $\Delta\sigma$ (if the fatigue test is carried on with constant stress value, $\Delta\sigma$g is zero), the fifth the number of cycles N_b for each block and the last column the final number of cycles N_f (when fracture or yield conditions occur or until $2{\cdot}10^6$cycles). Specimens have been stressed to failure or $2{\cdot}10^6$ cycles. Tests carried on by varying the stress level have been organized as follows, regarding the loading level respectively for the first and the last block: specimen C40_1, 250 and 550 MPa; specimen C40_3, 200 and 550 MPa; specimen C40_4, 200 and 600 MPa; specimen C40_5, 200 and 550 MPa; specimen C40_6, 380 and 590 MPa. For specimens C40_1, C40_3, C40_4 e C40_5 a block of 420 MPa has also been performed.

Damage parameters have been measured at the beginning of the test and then they have been monitored successively or simply during each fatigue block (hysteresis loop area, Young modulus, subtended area by the thermal profile) or at the end of each block (modal damping and natural frequency) .

Hysteresis loop area has been measured by means of an extensometer during the first part ($5{\cdot}10^3$ or 10^4 cycles, see Table 1) of the fatigue test (frequency 10 Hz, imposed by the Servohydraulic testing machine); on the basis of the acquired data, it has been possible to evaluate by means of a dedicated Matlab®program both hysteresis loop area, corresponding to the entity of the dissipated energy, and slope of the hysteresis loop branch for increasing loads, related to the material Young modulus.

At the same time, during the fatigue tests, the surface temperature of the specimen has been monitored by the infrared thermo tracer NEC TH7102WX, supported by the Mikrospec Real Time dedicated software. The subtended area by the thermal profile has been chosen in this paper as damage parameter and it has been calculated at the end of each loading block.

To perform the modal analysis at the end of each loading block in order to determine both modal damping and natural frequency, the specimen has been removed from the testing machine and then mounted in cantilever (free – clamped) boundary conditions, using a parallel bench vise for machine tool as constraint; the gripping force is sufficiently repeatable if the bench vise is locked by means of calibrated weights. This constraint system has been chosen, instead of the fatigue machine grips, having a high rigidity level compared to the specimen one, presenting a perfect decoupling of its modal properties compared to the specimen ones, lacking of elements (threads, springs, etc...) that can cause extra friction affecting damping measurements ([15], [16], [18]).

The input is given by an operator thanks to an instrumented hammer, that hit the frontal section of the specimen near the grip (40 mm from specimen edge). The output is measured by an accelerometer, mounted in the center of the frontal section. From the FRF (Frequency Response Function), expressed as Accelerance, Receptance is calculated, and modal parameters (modal damping and resonance frequency) are extracted for the second mode (according to [11]), using the Rational Fraction Polynomial Method [12]). Finally, measurement uncertainty range is statistically evaluated [12] on the basis of twice the standard deviation (i.e., 95% of confidence level) of twenty measurement replications for each session. A first measurement session is firstly performed on the unfatigued specimen, in order to assess the modal parameters value before fatigue test and thus repeated at the end of each block of cycles (more details are given in Table 1).

Table 1: Specimens and test conditions

Specimen	Test frequency [Hz]	σ_{max}[MPa]	$\Delta\sigma$[MPa]	N_b[-]	N_f[-]
C45_1	30	420	0	10^5	$2.00 \cdot 10^6$
C45_2	30	450	0	$5 \cdot 10^4$	$1.25 \cdot 10^6$
C40_1	30	Load Steps	50	$2 \cdot 10^4$	$1.80 \cdot 10^5$
C40_2	30	200	0	$5 \cdot 10^4$	$2.00 \cdot 10^5$
C40_3	30	Load Steps	50	$2 \cdot 10^4$	$1.80 \cdot 10^5$
C40_4	30	Load Steps	50	$3 \cdot 10^4$	$3.00 \cdot 10^5$
C40_5	30	Load Steps	50	$3 \cdot 10^4$	$2.70 \cdot 10^5$
C40_6	10	Load Steps	10	$5 \cdot 10^3$	$1.1 \cdot 10^5$

3 Results and discussion

Steels used for this work have been firstly characterized thanks to tensile tests (on at least 5 specimens) and Stair Case procedure [19], in order to evaluate ultimate strength R$_m$, yield stress $R_{p0.2}$ and fatigue limit σ_{D-1} in sinusoidal alternate traction – compression condition, with its scatter s. Such preliminary results have been reported in Table 2.

Table 2: Mechanical properties of steels.

Steel	R_m [MPa]	R$_{p0.2}$ [MPa]	σ_{D-1} [MPa]	s [MPa]
C45	800	500	239	9
C40	678	400	202	7

Results related to damage parameters monitoring are reported as follows.

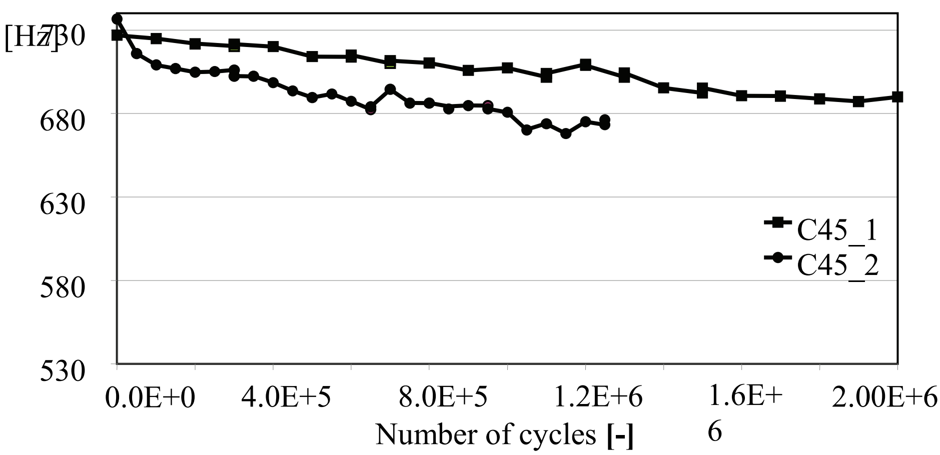

Figure 1: Resonance frequency variation during fatigue tests (C45 steel specimens)

Figures 1 and 2 show the evolution of the resonance frequency as a function of the fatigue cycles, respectively for C45 (loading blocks with constant stress level) and C40 steels (load steps); for sake of brevity, only the mean value of each measurement session has been represented.

It may me pointed out that for all cases and for both materials the resonance frequency tends to decrease together with the damage progression (only the mean value of each measurement session has been represented). This phenomenon appears strongly influenced by the entity of the stress. As a matter of fact, for specimens subjected to load steps (see Table 1) the frequency decreasing is weak in the

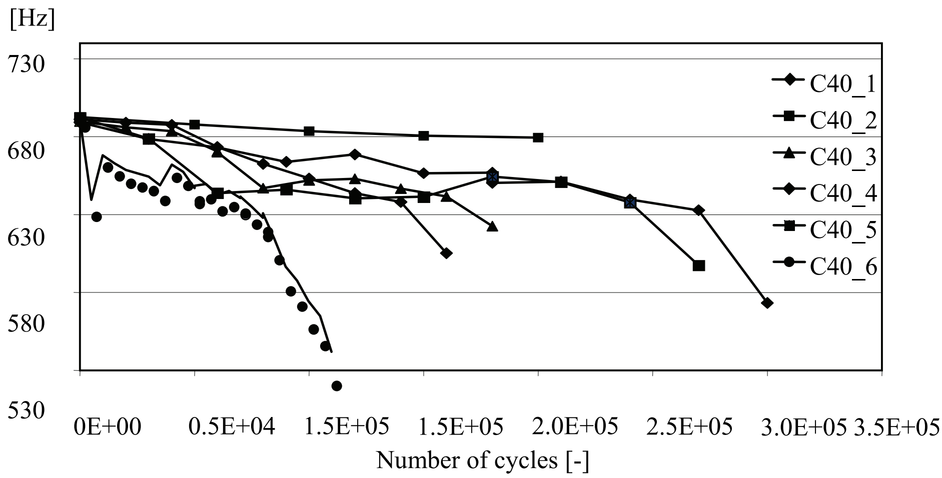

Figure 2: Resonance frequency variation during fatigue tests (C40 steel specimens)

first blocks, when the stress level is under or close to the fatigue limit, and becomes more and more relevant for stress levels higher than the fatigue limit and above all close to the yield zone.

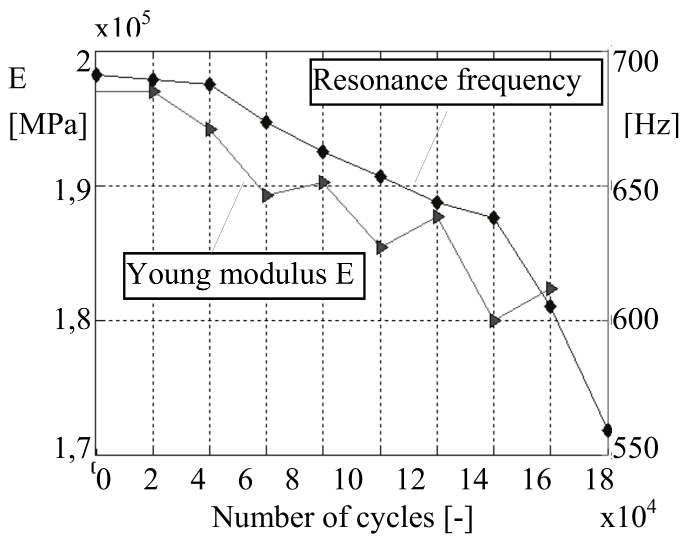

Figure 3: Resonance frequency and Young modulus E variation during fatigue tests (C40_1 steel specimens)

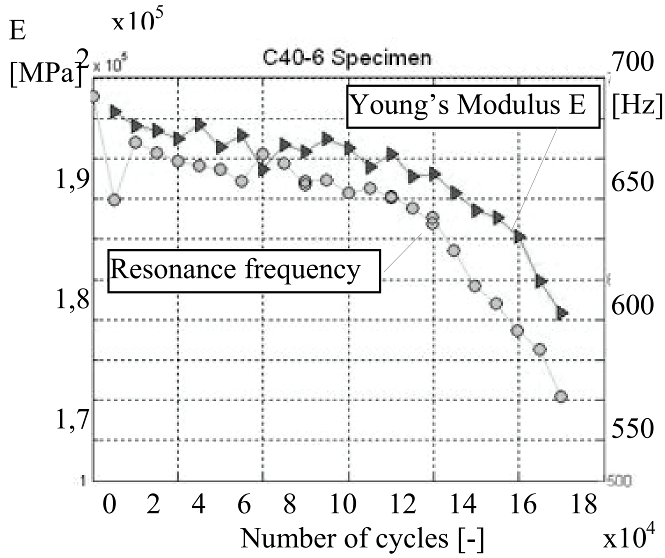

Figure 4: Resonance frequency and Young modulus variation during fatigue tests (C40_6 steel specimens)

Similar results may be observed for specimens subjected to repeated blocks of constant stress (see Figure 1); it may be observed that the most high loading level causes (C45_2) the most relevant frequency decreasing.

It has also to be remarked that, in order to reach the failure or $2{\cdot}10^6$ cycles, some specimens have been tested for more than one day (as an example, for specimen C45_1 eight days of tests have been required). In these cases, one session of twenty modal analysis acquisitions has been performed at the beginning of the new day, before the first block of cycles, aiming at verifying the eventual effect of the nightly pause; it may be noted that pauses may cause a weak frequency increase, as evidently indicated for specimens C45_2 ($1.50{\cdot}10^6$ cycles) and C40_4 ($1.80{\cdot}10^5$ cycles). A similar phenomenon has been previously emphasized by B.J. Lazan [4] for as concerns above all the damping energy and so called recovery in the present paper by analogy with [4].

The other mechanical parameter sensitive to damage is the Young modulus E.

As an example, Figures 3, 4 and 5 show respectively the evolution of both Young modulus (left y-axis) and resonance frequency (right y-axis) as a function of the number of cycles respectively for specimens C40_1, C40_6 and C45_1.

It may be observed that Young modulus and resonance frequency show a similar behavior, that is an evident decreasing with the damage progress. Also in this case, the decreasing slope appears substantially influenced by the entity of the fatigue stress.

For loading levels close to the yield stress (see experimental data related to last fatigue blocks for specimens C40_1 e C40_6, Figures 3 and 4 respectively), as confirmed by the measurement uncertainty analysis, the trend is very emphasized. For loading levels close to the elastic domain, the trend is weak (see experimental data related to first fatigue blocks for specimens C40_1 e C40_6, Figures 3 and 4 respectively) or completely absent (specimen C45_1, Figure 5).

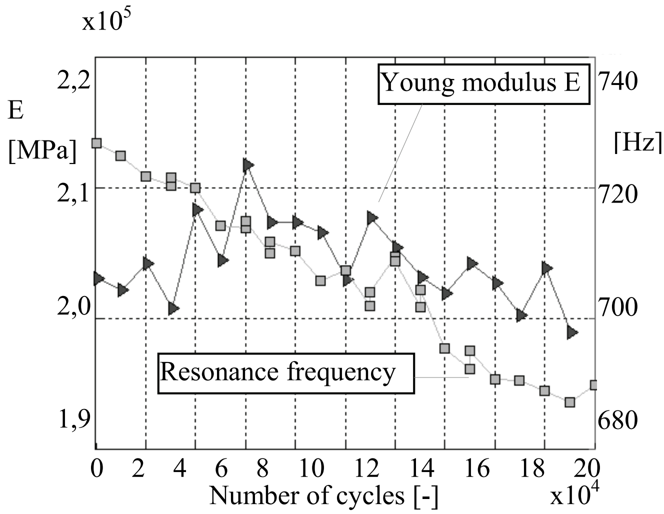

Figure 5: Resonance frequency and Young modulus variation during fatigue tests (C45_1 steel specimens)

Finally, it may be pointed out that the resonance frequency seems to be a more sensitive parameter with respect to the Young modulus for as concerns the evolution of the fatigue damage, both for the measurement stability and for the possibility to vary also for stress levels below or close to the fatigue limit.

Figures 6 and 7 show the monitoring of the so called dissipative parameters, modal damping z, hysteresis loop area and subtended area by the thermal profile.

In particular, these dissipative parameters (specimen C45_1, Figure 6 and specimen C40_1, Figure 7), normalized to be better represented in the same graph, are reported as a function of the number of cycles.

As indicated in Table 1, specimen C45_1 has been subjected to a constant stress value just higher than the fatigue limit; Figure 6 shows for this case a very weak variation of dissipative parameters, as reported in literature [2-4], appreciable only for the modal damping z. Only after $1.5 \cdot 10^6$ fatigue cycles it may be emphasized a decreasing of both modal damping and hysteresis loop area until the test stops at $2 \cdot 10^6$ cycles (as indicated in [19] the specimen may be considered as survived); in this case a hardening behavior may be hypothesized.

On the contrary, specimen C40_1 (Figure 7) has been subjected to load steps and a consistent increasing of dissipative parameters during the fatigue test may be pointed out, even if the measurement uncertainty has been taken into account.

In particular, a good agreement between hysteresis loop area and subtended area by the thermal profile may be observed. Also modal damping z shows an increasing trend, but not monotonic and so regular as the other two dissipative parameters.

Figure 8 showing the modal damping z (y-axis) as a function of the subtended area by the thermal profile (x-axis) may be able to further emphasize this phenomenon.

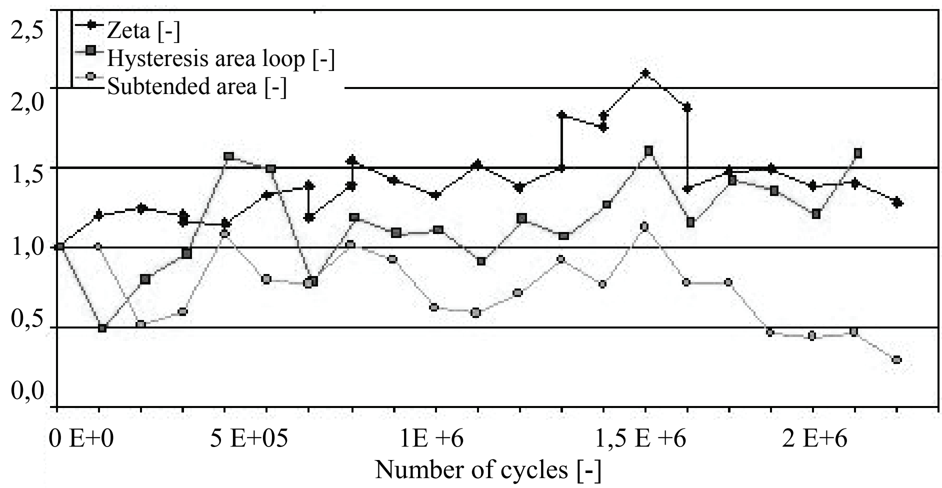

Figure 6: Modal damping, hysteresis loop area and subtended area by thermal profile variations during fatigue tests (C45_1 steel specimen)

Finally, thermal profiles utilised for the determination of the corresponding subtended area are reported in Figure 9, as an example for specimen C40_1. In particular, the x-axis reports the number of cycles for each loading block and the y-axis reports the thermal increment on the specimen surface. Two main effects may be observed in this figure. Firstly, the influence of the test frequency on the thermal

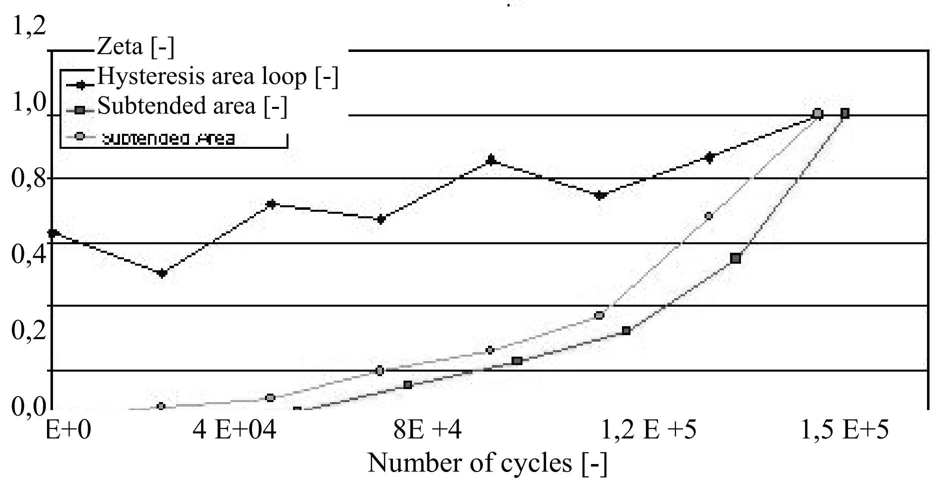

Figure 7: Modal damping, hysteresis loop area and subtended area by thermal profile variations during fatigue tests (C40_1 steel specimen)

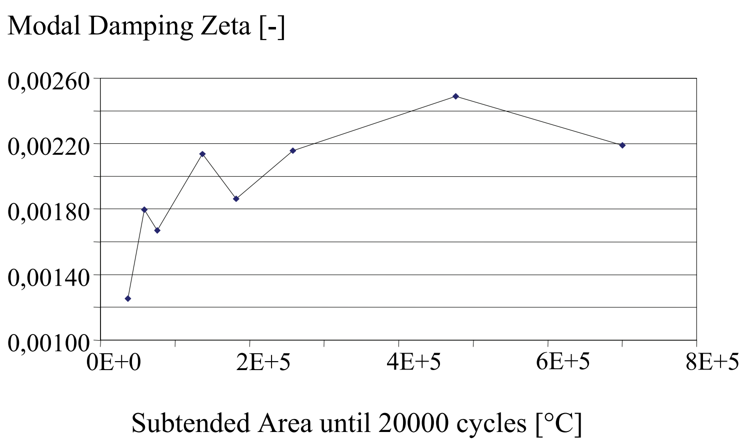

Figure 8: Subtended area up to 20000 cycles by thermographic acquisition vs modal damping (C40_1 steel specimen)

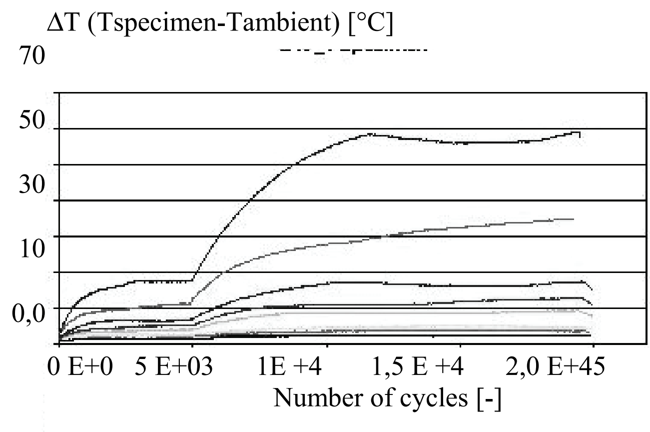

Figure 9: Thermal profiles (C40_1 steel specimen)

emission: a lower test frequency corresponds to a minor surface temperature on the specimen and viceversa. Then, the influence of the loading level on the thermal emission: higher is the fatigue stress, higher becomes the surface temperature.

4 Conclusions

On the basis of the experimental tests here presented and discussed, some conclusions may be drawn.

Firstly, a hybrid experimental technique has been set up to monitor and process some physical parameters, both mechanical (resonance frequency and Young modulus) and dissipative (modal damping, hysteresis loop area and subtended area by thermal profile), in order to characterize the fatigue damage in steel specimens.

Different experimental techniques have been utilized and integrated to this aim.

As an example, modal analysis is useful to measure resonance frequency and modal damping. Thermography allows to determine the surface temperature map of the specimen. A servohydraulic testing machine makes possible to measure both hysteresis loops area and Young modulus.

Furthermore, fatigue tests have been carried on in repeated loading blocks in order to make possible the monitoring of all damage parameters, both during the fatigue test (the specimen is mounted on the testing machine) and at the end of each block (the specimen is clamped on a dedicated testing device).

For as concerns mechanical parameters, the resonance frequency variation may be considered the more adequate to describe the fatigue damage, being meaningful if compared with the associated measurement uncertainty. The trend is the frequency value decrease (some dozens of Hz) with the number of cycles progression and this behavior appears strongly influenced by the load entity varying from the fatigue limit to the yield stress.

Modal analysis associated to fatigue tests seems to be a very promising technique to foresee and/or quantify the progress of damage in both materials and components.

Moreover, when it was possible, fatigue tests have been carried on in one day, but in some cases more working sessions were necessary. A peculiar phenomenon was then observed, that is the pause effect on the frequency value: if the test is interrupted for some hours or days, often the frequency measured at the beginning of the new test day is slightly higher that the previously one acquired. This effect has been here called recovery and it is maybe similar to the one reported in literature in similar conditions, involving in any case the damage phenomenon.

Also the Young modulus monitoring shows a similar behavior, even if a strong decreasing may be emphasised only close to the yield zone.

For as concerns dissipative parameters, a general increase may be observed with the number of cycle, but related phenomena are more difficult to discuss.

As an example, modal damping tends to increase, as reported in literature, but the detected variations are smaller than the expected ones, and measurement uncertainty still highly affects them. Below and near the fatigue limit, substantially there are not any meaningful changes, with the exception of specimens failed; above the fatigue limit, on the contrary, a modest augmentation has been observed.

A more evident increasing may be observed for both hysteresis loop area and subtended area by the thermal profile, above all in the case of load steps. Dissipative phenomena related to the fatigue damage may be emphasized by means of these parameters, making some more useful the thermographic approach being fast and easy to utilize.

As a matter of fact, the direct monitoring of hysteresis loops in high cycles fatigue is sometimes difficult, being strictly related to dedicated testing machines and to rigid experimental procedures. Thermography in general is more versatile.

In conclusion, from the damage identification point of view, the most promising parameters are resonance frequency and subtended area by thermal profile, defined as mechanical and dissipative respectively. They are above all very stable and related variations are so evident that measurement uncertainty could not substantially affect them.

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