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Procedia Structural Integrity 24 (2019) 651–657

Structural Integrity Procedia

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AIAS 2019 International Conference on Stress Analysis

A new approach to the analysis of fatigue parameters by thermal variations during tensile tests on steel

Eugenio Guglielmino, Giacomo Risitano, Dario Santonocito*

University of Messina, Contrada di Dio (S. Agata), 98166 Messina, Italy

Abstract

Fatigue properties are of fundamental importance and extremely time consuming to be assessed. The aim of this research activity is to apply the Static Thermographic Method (STM) during static tensile tests in order to correlate the surface temperature trend to the fatigue properties of a C45 steel. Full-field techniques are a powerful aid in the evaluation of the mechanical behaviour of the material and they can also accelerate the overall test time. Infrared Thermography (IR) allows the assessment of the fatigue properties of the material evaluating the energetic release during a tensile test even with a limited number of specimens. In this work, preliminary results about the influence of the applied stress rate on the thermal release of a medium carbon steel has been evaluated. The obtained fatigue limit has been compared to the literature data for the same steel. This research activity is the results of the collaboration between the University of Messina and other several Italian universities within the AIAS group on Energetic Methods.

Keywords: fatigue assessment; Static Thermographic Method; infrared thermography; C45.

1. Introduction

Traditional fatigue tests are extremely time consuming and require a huge number of specimens in order to obtain the fatigue properties of the material. An innovative approach, based on thermographic analyses of the temperature evolution during the fatigue tests, has been proposed for a rapid prediction of the fatigue limit and the S-N curve,

* Corresponding author. Tel.: +39 3396190552.
E-mail address: dsantonocito@unime.it

10.1016/j.prostr.2020.02.057

using a very limited number of tests: the Thermographic Method (TM) (La Rosa and Risitano, 2000). In a recent work, Risitano and Risitano (2013) proposed the Static Thermographic Method (STM) as a rapid procedure to derive the fatigue limit of the material evaluating the temperature evolution during a static tensile test.

In the last twenty years, the Infrared Thermography (IR) has been applied for the analysis of different materials subjected to several loading conditions: notched and plain steel specimens under static and fatigue tests (Ricotta et al., 2019; Rigon et al., 2019; Risitano and Risitano, 2013), laminated composites under tensile static loading (Vergani et al., 2014), polyethylene under static and fatigue loading (Risitano et al., 2018), short glass fiber-reinforced polyamide composites under static and fatigue loading (V. Crupi et al., 2015), steels under high cycle (Amiri and Khonsari, 2010; Curà et al., 2005; Meneghetti et al., 2013) and very high cycle fatigue regimes (V Crupi et al., 2015; Plekhov et al., 2015).

The aim of this research activity is the application of the Static Thermographic Method (STM) during static tensile tests for the fatigue assessment of a medium carbon steel of the class C45. Tensile tests were carried out and infrared thermography has been adopted during all static tests in order to assess the influence of the stress rate on the energetic release of the material. This research activity is part of the collaboration between the University of Messina and several others Italian universities within the AIAS group on Energetic Methods.

Nomenclature

c	specific heat capacity of the material [J/kg.K]
K_m	thermoelastic coefficient [MPa^{-1}]
R	load ratio
t	test time [s]
T, T_i	instantaneous value of temperature [K]
T_0	initial value of temperature estimated at time zero [K]
α	thermal diffusivity of the material [m^2/s]
ΔT_s	absolute surface temperature variation during a static tensile test [K]
ΔT_1	estimated value of temperature for the first set of temperature data [K]
ΔT_2	estimated value of temperature for the second set of temperature data [K]
ρ	density of the material [kg/m^3]
σ	stress level [MPa]
σ_D	critical macro stress that produces irreversible micro-plasticity [MPa]
σ_{lim}	fatigue limit estimated with the Static Thermographic Method [MPa]
σ_1	uniaxial stress [MPa]
$\dot{\sigma}$	stress rate [MPa/min]

2. Theoretical background

During a uniaxial traction test of common engineering materials, the temperature evolution, detected by means of an infrared camera, is characterized by three phases (Fig. 1): an initial approximately linear decrease due to the thermoelastic effect (phase I), then the temperature deviates from linearity until a minimum (phase II) and a very high further temperature increment until the failure (phase III).

In adiabatic conditions and for linear isotropic homogeneous material, the variation of the material temperature under uniaxial stress state follows the Lord Kelvin's law:

$$\Delta T_s = -\frac{\alpha}{\rho \cdot c} T \sigma_1 = -K_m T \sigma_1 \tag{1}$$

where K_m is the thermoelastic coefficient.

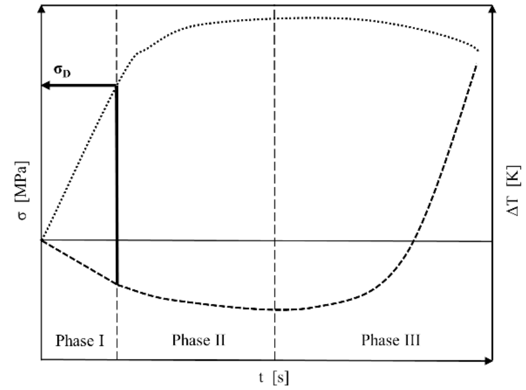
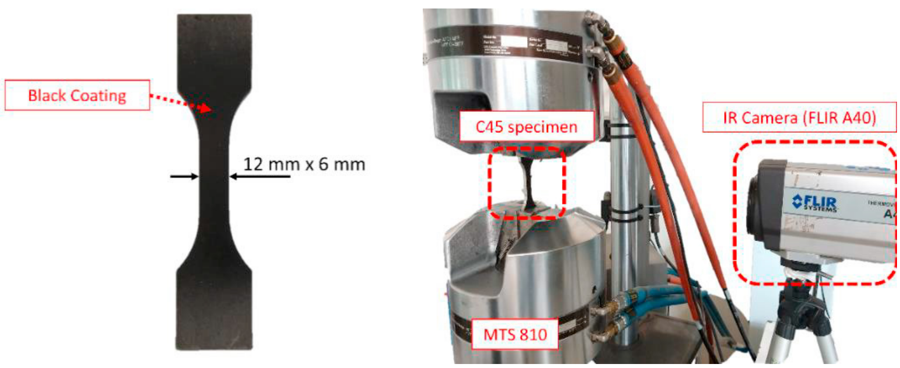


Fig. 1. Temperature trend vs. load during a static traction test.

The use of high precision IR sensors allows to define experimental temperature vs. time diagram during static tensile test in order to define the stress at which the linearity is lost. Clienti et al. (2010) for the first time correlated the damage stress σ_D related to the first deviation from linearity of ΔT temperature increment during static test (end of phase I) to the fatigue limit of plastic materials. Risitano and Risitano (2013) proposed a novel procedure to assess the fatigue limit of the materials during monoaxial tensile test. If it is possible during a static test to estimate the stress at which the temperature trend deviates from linearity, that stress could be related to a critical macro stress σ_D which is able to produce in the material irreversible micro-plasticity. This critical stress is the same stress that, if cyclically applied to the material, will increase the microplastic area up to produce microcracks, hence fatigue failure.

3. Materials and methods

Static tensile tests were carried out on specimens made of C45 steel. The specimens have a dog bone shape (Fig. 2a) with a nominal cross section of 12 mm x 6 mm. All the tests were performed with a servo-hydraulic load machine MTS 810 (Fig. 2b). In order to assess the influence of the load velocity on the energetic release of the specimen, the static tests were conducted under load control adopting three different stress rate: 200 MPa/min, 400 MPa/min and 800 MPa/min. The infrared camera FLIR A40 was used, with a sample rate of 2 image per second, in order to monitor the specimen's surface temperature.



(a) (b)

Fig. 2. (a) dog-bone specimen geometry; (b) experimental setup.

The load and temperature data coming from the tests were analysed adopting an algorithm implemented via Matlab® scripts. The specimen rupture instant has been taken as the reference time for synchronizing the data. In order to clean the temperature signal from outliers and to enhance the trend of the thermoelastic effect during static tests, a locally weighted scatter plot smooth filter (*rlowess*) with a data span of 10%, already implemented in Matlab®, was chosen. This kind of filter uses locally linear regression to smooth data defining a span in which each data point assumes a weight depending on its distance from the data to be smoothed.

4. Results and discussion

A series of static tests has been conducted on three specimens per stress rate, for a total number of nine tensile tests. In this kind of test, the stress rate has to be choose properly in order to assure adiabatic conditions. The applied stress is reported versus the specimen's surface temperature variation, estimated as the difference between the instantaneous temperature and the initial temperature of the surface recorded at time zero ($\Delta T = T_i - T_0$). The temperature data has been filtered with a rlowess filter in order to reduce the outliers and highlight the thermoelastic trend. For all of the adopted stress rate is reported only one graph as an example, considering that the other tests exhibit the same thermal behaviour.

For the first applied stress rate of 200 MPa/min, the temperature trend has been reported in Fig. 3. It is not easy to distinguish the different phases and the change in the slope of the temperature signal. A possible explanation could be addressed to the slow test velocity which allows the specimen to exchange heat with the surrounding environment, i.e. the energetic release is not adiabatic.

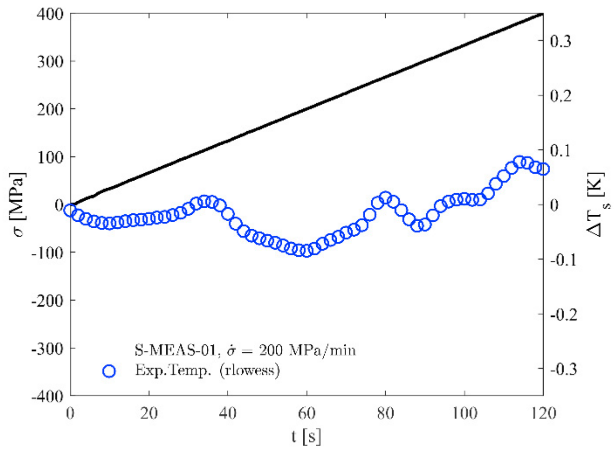


Fig. 3. Temperature evolution vs. applied stress during static tensile test, with stress rate of 200 MPa/min.

Considering an applied stress rate of 400 MPa/min (Fig. 4), in the initial part of the ΔT-t curve it is possible to distinguish the linear trend of the temperature, then it deviates from the linearity reaching a plateau region. It is possible to draw two linear regression line, the former for the first linear phase (early stage of the temperature signal, ΔT_1 fit point series) and the latter for the second phase (last stage before the sudden increase in the temperature signal, ΔT_2 fit point series), not taking into account the temperature values near the slope change (Experimental Temperature series). Solving the system of equations, it is possible to determine the intersection point of the two straight lines. The corresponding value of the applied stress could be related to the macroscopic stress that leads to the irreversible plasticization phenomena in the material. For the stress rate of 400 MPa/min, the limit stress has been evaluated on three tests, obtaining a value equals to 219.4±6.1 MPa.

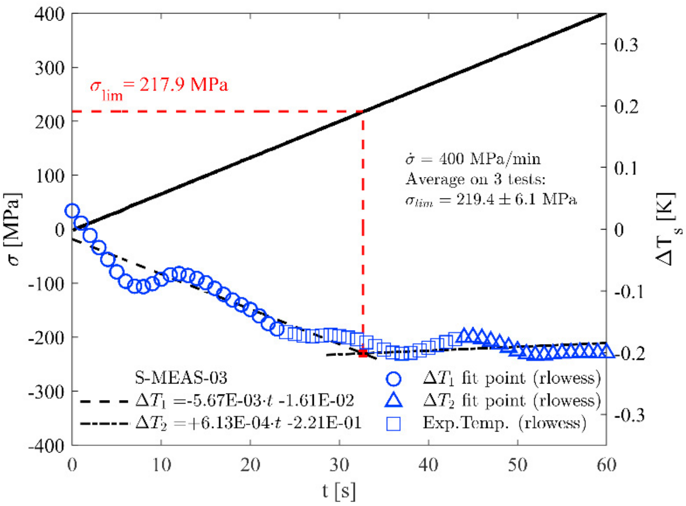


Fig. 4. Temperature evolution vs. applied stress during static tensile test, with stress rate of 400 MPa/min.

Considering a stress rate of 800 MPa/min (Fig. 5), the energetic release is faster than the previous two cases and it is difficult to distinguish in a clear way the two different temperature phases (ΔT_1 and ΔT_2 fit point series), although it is possible to draw two regression lines and make their intersection. The value of the limit stress found on the three tests is equals to 220.2±7.4 MPa.

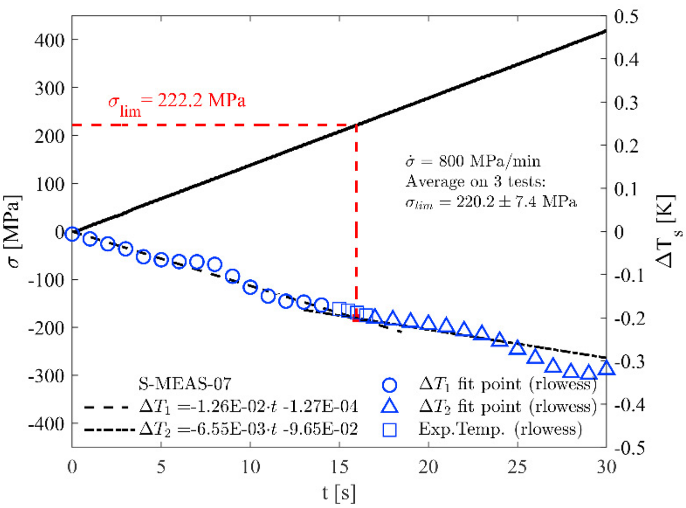


Fig. 5. Temperature evolution vs. applied stress during static tensile test, with stress rate of 800 MPa/min.

The stress limit obtained by means of the Static Thermographic Method could be compared with the fatigue limit obtained with alternate traction-compression tests, conceivable as the more damaging dynamic load condition for the material. In a work by Szala and Ligaj (2016), the S-N curve of a C45 steel, obtained with constant load tests and load ratio R= -1, has been reported. The fatigue limit evaluated with a 50% probability of survival at $2x10^6$ cycles is equals to 210 MPa. Curà and Gallinatti (2011) for the same steel report a fatigue limit, obtained by means of Stair Case procedure with R= -1, equals to 239±9 MPa. The values of the stress limit, for a stress rate equals to 400 MPa/min and 800 MPa/min, fall within the previous reported literature values of fatigue limit, hence the Static

Thermographic Method could be adopted as a rapid and time-saving procedure for the assessment of the fatigue properties of the materials.

5. Conclusion

In this work the energetic release during a tensile test of a C45 steel has been evaluated. This research activity is part of the collaboration between the University of Messina and other several Italian universities within the AIAS group on Energetic Methods. The IR camera allowed the application of the Static Thermographic Method monitoring the specimen's surface temperature. The influence of the applied stress rate on the energetic release has been evaluated, in particular:

- For a stress rate of 200 MPa/min the energetic release is not adiabatic and it has not been possible to observe a change in the temperature slope.
- Considering a stress rate of 400 MPa/min the limit stress has been evaluated as the stress level at which the temperature deviates from its linear trend, obtaining a value of 219.4±6.1 MPa.
- For a stress rate of 800 MPa/min, even if more difficult, it is still possible to distinguish a stress limit equals to 220.2±7.4 MPa.

The obtained values of the stress limit have been compared with fatigue limit taken from literature for the same steel showing good agreement. Further comparisons with other energetic methodologies and with traditional fatigue tests have to be carried out. The Static Thermographic Method is a rapid test methodology able to predict the fatigue properties of the materials from a static test, even with a limited number of specimens and in a short amount of time.

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