Evaluation of the Energetic Release During Tensile tests in Notched Specimens by means of Experimental and Numerical Techniques

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Abstract. Static Thermographic Method is a rapid test procedure able to predict the fatigue limit of the material evaluating the end of the thermoelastic phase during a static tensile test. In order to investigate the energetic release of the material, experimental tests have been carried out on double edge steel notched specimens. During the test, the surface temperature was monitored with an infrared camera and the true stress-strain curve of the material was retrieved. Numerical simulations have been carried out to predict the temperature evolution of the material under monotonic load. The relationship between the elasto-plastic behavior and the energetic release has been investigated comparing numerical and experimental data. The rise of irreversible plastic deformation severely affects the temperature trend introducing an additional heat amount that leads to a deviation from the linearity of the thermoelastic effect. The analysis of the temperature evolution during a static tensile test may be adopted as a novel approach to relate the local stress state with a macroscopic stress value that introduces in the material the first micro plasticization.

1. Introduction

Fatigue is a dissipative degradation phenomenon which adopts only a very small portion of the provided external mechanical work to activate internal material transformations. The large part of the external energy is dissipated as heat into the surrounding environment. Moving from this consideration, it is possible to assesses the energetic release of a material under fatigue loads and correlate it to its fatigue life. One of the simplest and adopted technique is the Infrared (IR) Thermography, a non-contacting measuring technique. Among the IR techniques, the Thermographic Method (TM) [1], proposed for the first time in 1989, has been adopted to evaluate the fatigue limit of the material in a short amount of time. A further evolution of the thermographic approach is represented by the Static Thermographic Method (STM) [2]. It has been proposed as a rapid and economic procedure to estimates the fatigue limit of such a material analyzing the surface temperature trend of specimens subjected to static loads.
Their use has already shown that the thermal analysis allows the estimation of the fatigue limit of the material with a very small number of specimens dealing with plain and notched steel specimens under static and fatigue tests [2–10], laminated composite under tensile static loadings [11–13], polyethylene under static and fatigue loadings [14,15], short glass fiber-reinforced polyamide composites under static and fatigue loadings [16], steels under high cycle [8,10,17,18] and very high cycle fatigue regimes [6,19] and additive manufactured components [20].

In this work, by side of these experimental techniques, the thermal behavior of the material during a static tensile test has been simulated by finite element analysis in order to assess the effect of irreversible plastic deformations arise within the specimen to its global energetic release.

2. Theoretical background

2.1. Temperature trend during static tensile test

In this section, a simplified temperature model for engineering materials under static tensile condition is exposed. It is based on the fundamental assumption that fatigue failures occur within the material where the local stress distribution, amplified by structural or superficial micro defects, is capable of producing local micro plastic deformation [2]. The local stress state can be linked to a macroscopic nominal stress value (load/area) that introduce in the material the first micro plasticization.

The relationship between the applied stress, or strain, and the corresponding temperature change in solid material \( \Delta T \) consist of two contributions due to a thermoelastic \( \Delta T_e \) and a thermoplastic \( \Delta T_p \) effect (Equation (1)) [21].

\[
\Delta T = \Delta T_e + \Delta T_p
\]  

(1)

The thermoelastic effect is a well known phenomenon adopted in stress analysis to evaluate the distribution of the first invariant stress tensor \( I_{1\sigma} \), i.e. the sum of the principal stresses [22,23]. Under adiabatic conditions and for a linear isotropic homogeneous material, the variation of the material temperature, follows the Lord Kelvin’s law:

\[
\Delta T_e = -\frac{\alpha}{\rho \cdot c} I_{1\sigma} = -K_m I_{1\sigma}
\]  

(2)

Where \( K_m \) is the thermoelastic coefficient, calculated from the material linear elastic coefficient \( \alpha \), the density \( \rho \) and the specific heat \( c \).

After the material locally reaches a stress condition beyond its yielding stress, the irreversible plastic deformations lead to an increase in temperature. From the first principle of thermodynamics (energy conservation), the rise in internal energy (first member of Equation (3)) could be addressed to the heat generated by plastic deformation (second member of Equation (3)).

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial Q}{\partial t}
\]  

(3)

The generated heat due to plastic deformation can be linked to the mechanical energy by means of the Taylor-Quinney coefficient \( \beta \), defined as the percentage of plastic deformation energy dissipated into heat \( Q = \beta W_p \). Despite this coefficient varies in different metallic materials [24], for sake of simplicity it can be assumed constant and equal to 0.9. Under these hypothesis, the temperature increment due to plastic deformation can be estimated with Equation (4), considering the plastic deformation \( \varepsilon_p \) performed from a strain level \( \varepsilon_1 \) to a strain level \( \varepsilon_2 \).

\[
\Delta T_p = \frac{1}{\rho \cdot c} \int Q dt = \frac{\beta}{\rho \cdot c} \varepsilon_2 \sigma d\varepsilon_p
\]  

(4)

In the elastic phase the temperature experiences a linear decrease due to the thermoelastic effect. If a plasticity condition is reached locally in some internal defect point of the material, Equation (1) is no longer valid and a heat amount leads to a deviation from the linear trend.
2.2. Static Thermographic Method

During a uniaxial traction test of common engineering materials, the temperature evolution, detected by means of an infrared camera, is characterized by three phases (Figure 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).

Under uniaxial stress state and in adiabatic test conditions, Equation 1 can be simplified as:

$$\Delta T = -K T \sigma$$

Figure 1. Temperature trend during a static tensile 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. In 2010, Clienti et al. [25] for the first time correlated the damage stress $\sigma_{\text{lim}}$ related to the first deviation from linearity of $\Delta T$ temperature increment during static test (end of phase I) to the fatigue limit of plastic materials. Risitano and Risitano [2] 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 $\sigma_{\text{lim}}$ 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

The material under study was a medium carbon steel AISI 1035 and two kind of specimen geometries were adopted (Figure 2a): a plain geometry and a blunt V-notched geometry with opening angle $2\alpha = 120^\circ$ and fillet radius $\rho = 2$ mm. All the tests were performed with a servo-hydraulic axial load machine INSTRON 8854 with maximum load capacity of 250 kN. In order to apply the TM and STM during fatigue and tensile tests, infrared thermography was adopted to monitor the evolution of the specimen surface temperature. During all the tests, the maximum temperature value of a rectangular measurement area, placed in the vicinity of the two specimen notched section (Figure 2b), has been recorded. The infrared camera FLIR A40, with a temperature measurement range between -40°C and +120°C was used. The specimens were coated with a black paint to increase the thermal emissivity of the material up to 0.98. A static tensile test under displacement control (5 mm/min) was
performed in order to obtain the material true stress-strain curve adopting the plain specimen geometry (Figure 3a).

Figure 2. a) specimen geometries; b) IR camera spot on the specimen V-notch area.

The Digital Image Correlation (DIC) technique was adopted to monitor the superficial deformation of the specimen with two cameras (resolution of 4000 x 3000 pixels, focal length of 50 mm). The system accuracy for the strain measurement is up to 0.01%, and the images were acquired at 1 Hz. The ARAMIS 3D 12 M system was used to analyze the strain field of the specimen surface (Figure 3b).

Figure 3. True stress-strain curve and thermos-mechanical properties for AISI 1035; b) DIC software elaboration.

A series of three fatigue tests was performed on the notched geometry adopting a stress ratio $R=-1$ and a frequency $f=20$ Hz. A fatigue test was performed adopting a step-wise increase of the stress ($\Delta \sigma = 42$ MPa), ranging from 40 MPa up to 250 MPa with a number of cycle per block $\Delta N = 20000$. The other two fatigue test were performed under constant amplitude stress, respectively of 200 MPa and 260 MPa. The sample rate of the infrared camera was set to 1 image per minute.
A second series of static tensile tests was performed on the notched specimens under stress control in order to assess the influence of the stress rate on the energetic release of the material. Three different load application speeds were considered: 60, 120 and 180 MPa/min. The infrared camera sample rate was set to 1 image per second; a total number of 5 tests were performed.

A nonlinear structural finite element model was implemented adopting Ansys APDL in order to estimate the thermal behavior under a static tensile test of the notched specimens by means of the thermal model presented in section 2.1. The elasto-plastic material behavior was modeled adopting a multilinear isotropic hardening plasticity model with true stress-strain data from experimental tests. For the notched specimen (Figure 4), only 1/8th of the geometry was modeled, taking advantage of the specimen symmetries. Hexahedral 20-node SOLID186 elements were chosen and, after a calibration procedure, a number of 10,000 elements were adopted. Symmetric boundary conditions were applied to the geometry, while the tensile force was equally distributed on the grip section nodes. The first stress invariant and the plastic work per unit volume of the node belonging to the blunt V-notch volume were considered in order to evaluate the energetic release of the specimen.

![Figure 4. Structural FE model for predicting the thermal behaviour of the specimen by mean of the thermal model of section 2.1.](image)

### 4. Results and discussion

#### 4.1. Fatigue tests

During the fatigue tests, the evolution of the specimen surface temperature has been analyzed in order to apply the TM. Given the fact that the temperature trend during all the tests does not show a stabilization phase, in the following analysis the initial thermal gradient $\Delta T/\Delta N$ has been considered.

The first fatigue test was performed with a stepwise increase of the stress level $\Delta \sigma$ under fully reversed load condition. In Figure 5 the temperature trend vs. the number of cycles and the experimental stress level have been reported. For stress level below 208 MPa no significant increase in the temperature trend can be appreciated. As the stress level reaches 208 MPa, a rapid temperature increment can be noticed, with a thermal gradient of $5.7 \times 10^{-5}$ K/cycle. For the higher stress level of 250 MPa a very high further temperature increment is exhibited, with a thermal gradient of $2.1 \times 10^{-4}$ K/cycle, until the specimen failure.
Figure 5. Stepwise fatigue test.

Considering that the temperature trend of the stepwise fatigue test has been shown a significant increment moving from 167 MPa and 208 MPa, it is reasonable to think that the fatigue limit of the material under study falls within this stress levels. According to the previous argument, the remaining two fatigue tests have been performed under constant amplitude stress levels above 200 MPa. The first constant amplitude fatigue test carried out with a stress level of 260 MPa (Figure 6a). Even in this case the temperature signal did not shown a stabilization phase, hence the thermal gradient has been estimated (1.2x10^{-4} K/cycle, up to 14000 cycles). The second constant amplitude fatigue test has been carried out with a stress level of 200 MPa (Figure 6b), showing a thermal gradient of 3.41x10^{-5} K/cycle up to 10000 cycles, where the thermal exchange of the specimen with the surrounding environment can be assumed adiabatic. Generally, the higher the stress, the higher the thermal gradient during a fatigue test.

Figure 6. Constant amplitude fatigue test: a) 260 MPa; b) 200 MPa.

In order to estimate the fatigue limit by means of the TM, the thermal gradients of the three fatigue tests have been reported vs. the square of their corresponding stress level (Figure 7). It is possible to
evaluate the fatigue limit performing the linear regression of the data and making the intersection of it with the stress axis. A value of $\sigma_{0\ TM}=174.6$ MPa has been found for the fatigue limit assessed by the TM.

![Fatigue Tests](image)

$\sigma_{0\ TM}=174.6$ MPa

$\Delta T/\Delta N = 4.63 \times 10^{-9} \sigma^2 - 1.41 \times 10^{-4}$

**Figure 7.** Fatigue limit assessed by TM.

4.2. Energetic release during tensile tests

The specimen surface temperature evolution during static tensile tests has been recorded by means of an IR camera in order to apply the STM. The difference between the instantaneous temperature and the initial temperature of the surface at time zero ($\Delta T = T_i - T_0$) has been related with the applied stress synchronizing the load data from the servo-hydraulic axial load machine with the one from the IR camera. The instant of failure of the specimen has been taken as the reference. In order to better identify the different phases of the surface temperature evolution and highlight the thermoelastic trend, a lowpass filter has been used to process the data, considering a data span of 10%.

The first three static tests have been carried out at three different applied stress rates in order to find out the best test parameter to meet the adiabatic condition. From the data acquired, the best results are achieved with an applied stress rate of 120 MPa/min, which has been chosen to carry out the remaining two static tests. For the other two applied stress rates (60 and 180 MPa/min) the effect in terms of decrease in surface temperature seems to be mitigate. This can be addressed, for the lowest rate, to the possible exchanged heat with the surrounding environment due to the longer test time while, for the faster rate, the excessive reduced time of the test do not allow the material to manifest the temperature evolution clearly in each one of its phases.

In Figure 8 are reported the temperature trends of the three tensile tests performed at 120 MPa/min. The thermoelastic phase is clearly distinguishable as well as the deviation from the linearity entering in the thermoplastic region and the further rapid temperature increment before the final failure. For each test, it has been possible to draw the linear regressions ($\Delta T_1$ and $\Delta T_2$ temperature series) and make their intersection evaluating the limit stress. The average value of the limit stress evaluated on the three tests is $\sigma_{lim}=177.4\pm0.6$ MPa. According to the considerations already done in section 2, this stress value can be thought as the macroscopic stress that lead to the first plasticization phenomena in the material. The limit stress value found by means of the STM is really close to the fatigue limit assessed by the TM.
4.3. Prediction of the temperature trend

The thermal behavior of the notched specimens during a static tensile test has been modelled through a 3D elasto-plastic FE analysis. For each node of the volume surrounding the notch, the first stress invariant $I_1$, i.e. the sum of the three principal stresses, and the plastic work per unit volume $W_p$ have been evaluated. The results coming from the structural analysis have been adopted as input for the temperature model presented in section 2.1, evaluating the thermal contribution due to the elastic and plastic material behavior, and averaging it. The experimental and FE temperature trends have been reported in Figure 9 vs. the stress level, referred to the specimen reduced section, for the three static tensile tests performed with a stress rate of 120 MPa/min. For the FE temperature model, the thermoelastic constant $K_m$ (3.14x10^{-12} Pa$^{-1}$) as calculated by literature data has been adopted [26]. Generally, the simulated thermal trend follows the experimental temperature behavior, especially near the failure stress, where it experiences a rapid increment till breakage. For the first and last tensile tests
(Figure 9a, c), the FE simulations overestimates the temperature trend, while for the second tensile test (Figure 9b) the simulated temperature trend well fit the experimental behavior.

![Graph](image)

**Figure 9.** Experimental vs. FE thermal behavior of notched AISI 1035 specimens during a static tensile test.

As regard the experimental thermoelastic constant $K_m$, it has been evaluated on the three notched geometries. The linear regression of the experimental temperature data vs. the nominal stress up to 100 MPa, where the temperature trend is expected to be perfectly linear, has been performed and the value have been reported in Table 1. The thermoelastic constant values for the first and third tests are nearly similar. On the other hand, the second tensile test thermoelastic constant shows a different value compared to the previous two tests.

Discrepancies are also present for the limit stress, indeed the first plasticization in the FE model appear for a nominal stress level of 290 MPa, higher compared to the experimental value of 177 MPa. These differences in the rise of plastic phenomena, as well as of the thermoelastic coefficient may be addressed to the presence of local micro defect within the material near the notch area (i.e. inclusion or
machining defects) that may alter the local mechanical behavior and, hence, also the thermal behavior of the material.

| Table 1. | Thermoelastic constant for the static tensile tests. |
|----------|-----------------------------------------------|
| Test     | S-120-02 | S-120-04 | S-120-05 |
| $K_m [\text{Pa}^{-1}]$ | 9.06x10$^{-12}$ | 2.28x10$^{-12}$ | 9.00x10$^{-12}$ |

5. Conclusion

In the present work, the fatigue assessment of medium carbon steel AISI 1035 blunt V-notch specimens has been performed adopting several energy based methods: Thermographic Method and Static Thermographic Method.

Experimental fatigue tests have been performed monitoring the specimens surface temperature in order to estimate in a rapid way the fatigue limit of the material by means of the TM. Static tensile tests have been performed adopting several stress rate to assure adiabatic test condition, in order to evaluate the first deviation from the thermoelastic trend of the temperature signal. Elasto-plastic numerical simulations have been performed in order to predict the specimen thermal behavior under static tensile test and compare it to the experimental temperature trend, showing how the local defect on the notch area can severely affect the fatigue strength of the material.

The energy based methods can be adopted in order to estimate and predict in a rapid way the fatigue life of notched mechanical components.

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