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Energetic approach for the fatigue assessment of PE100

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Abstract

In the recent years, polyethylene, especially with its highest standard PE100, has been adopted in several industrial fields due to its good mechanical resistance and lightness, combined with low cost. On the other hand, the different manufacturing and working conditions severally affects its mechanical performances, hence extremely time-consuming fatigue tests have to be carried out in order to assess them. The Static Thermographic Method (STM) has been applied to a large set of engineering materials in order to evaluate the limit stress at which the material's surface temperature trend deviates from the linearity during a static traction test. In the present work, the STM is applied on PE100 in order to investigate its fatigue properties. The limit stress is compared with the fatigue limit obtained by traditional fatigue tests showing good agreement. The STM is a rapid tests procedure able to derive the fatigue properties of the material in a very short amount of time and with a limited number of specimens.

Keywords: polyethilene; fatigue assessment; Static Thermographic Method.

1. Introduction

Polyethylene is one of the most adopted materials for pressure pipe applications, especially for water and gas distribution, thanks to its low cost, lightness and good corrosion resistance. Several factors may affect the reliability and safety of pressure pipe (Saghi, 2015), hence it is important to assess the long-term mechanical performance of such system (Janson et al., 2005; Khademi-Zahedi, 2019; van Zyl and Clayton, 2005), considering a required lifetime of 100 years for the new generation of pipe materials under normal operation conditions.

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Despite numerous studies conducted on the fatigue behavior of polymer materials, few studies have been performed in order to investigate the fatigue properties of high density PE100. Bourchak and Aid (Bourchak and Aid, 2017) conducted an experimental test campaign under constant and variable amplitude fatigue loads. They adopted several damage models, such as Miner's rule, stress-based and energy based damage model, in order to predict the cumulative fatigue damage under variable amplitude loads. Deveci and Fang (Deveci and Fang, 2017) discussed the correlations of molecular weight, molecular weight distribution, short chain branching and rheological properties of different polyethylene materials with their slow crack growth resistances obtained from the strain hardening and crack round bar tests and their correlations with notched pipe tests. In (Djebli et al., 2016), an experimental analysis for determining the fatigue strength of HDPE-100 under cyclic loading is presented. The curve of cumulative fatigue damage versus number of cycles (D-N) was deduced from stiffness degradation. Based on the three-stage damage trend, the remaining fatigue life is numerically predicted by considering a double term power damage accumulation model. This model is found to be accurate, both in modeling the rapid damage growth in the early life and near the end of the fatigue life.

Fatigue is a dissipative process that requires a huge amount of time and a large number of specimens in order to be assessed, hence the infrared thermography (IR) could be a valid aid in its investigation. It has been applied on different materials subjected to several loading conditions: notched and plain steel specimens under static and fatigue tests (Guglielmino et al., 2020; 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; P. Corigliano et al., 2019; Pasqualino Corigliano et al., 2019; Curà et al., 2005; Meneghetti et al., 2013) and very high cycle fatigue regimes (V Crupi et al., 2015; Plekhov et al., 2015).

In 2000, La Rosa and Risitano (La Rosa and Risitano, 2000), proposed the Thermographic Method (TM) as an innovative approach based on thermographic analyses of the temperature evolution during the fatigue tests in order to predict the fatigue limit and the S-N curve (Fargione et al., 2002). In 2013, Risitano and Risitano 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.

The aim of this research activity is the application of the STM during static tensile tests on high-density PE100. Tensile tests were carried out and IR thermography has been adopted during all the static tests in order to evaluate the energetic release of the material. The obtained value has been compared with the fatigue limit derived from traditional fatigue test.

Nomenclature

c	specific heat capacity of the material [J/kg.K]
E	Young's Modulus [MPa]
f	frequency test [Hz]
N_A	run-out number of cycles
k	inverse slope
K_m	thermoelastic coefficient [MPa^{-1}]
R	stress ratio
t	test time [s]
T, T_i	instantaneous value of temperature [K]
T_0	initial value of temperature estimated at time zero [K]
v	displacement velocity [mm/min]
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, σ_1	stress level, uniaxial stress [MPa]
σ_D	critical macro stress that produces irreversible micro-plasticity [MPa]
σ_{lim}	fatigue limit estimated with the Static Thermographic Method [MPa]
$\sigma_{0,50\%}$	fatigue limit with 50% probability of survival [MPa]

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 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:

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

where K_m is the thermoelastic coefficient.

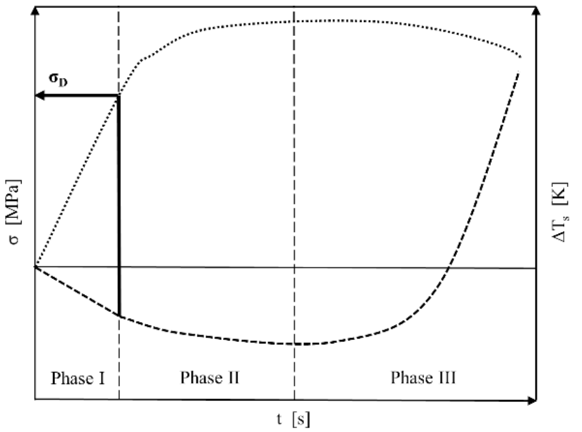


Fig. 1. Temperature trend vs. load during a static traction test.

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. In (Clienti et al., 2010), the authors 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

The material under study was a high-density polyethylene PE100. According to the ISO 527 standard, Type 1A dog bone flat specimens were obtained by injection molding process with a nominal cross section area of 10x4 mm^2. A series of static tensile tests was performed on 3 specimens with a servo-hydraulic load machine ITALSIGMA 25kN (Fig. 2) adopting a crosshead rate equal to 5 mm/min under constant temperature and relative humidity (23°C and 50% RH). During all the tests the surface temperature of the specimen was monitored with an IR camera adopting a sample rate of 1Hz. In Table 1 the mechanical properties of the material retrieved by the Authors are compared with the datasheet values showing a good agreement. The nominal tensile stress at yield and tensile modulus, as reported by the manufacturer datasheet, are obtained adopting different crosshead speed compliant with ISO 527 standard; while a unique crosshead speed was adopted by the Authors.

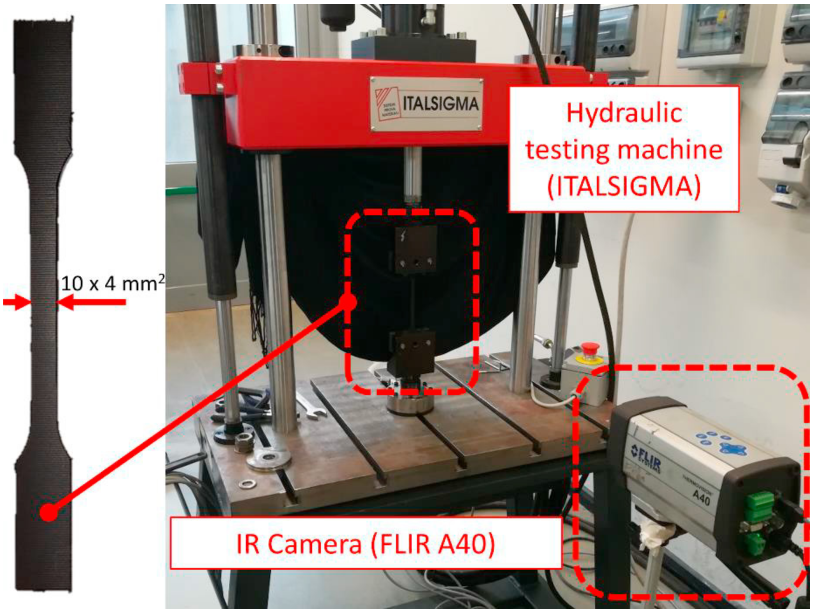


Fig. 2. Experimental setup.

Table 1. Comparison of the mechanical properties of PE100.

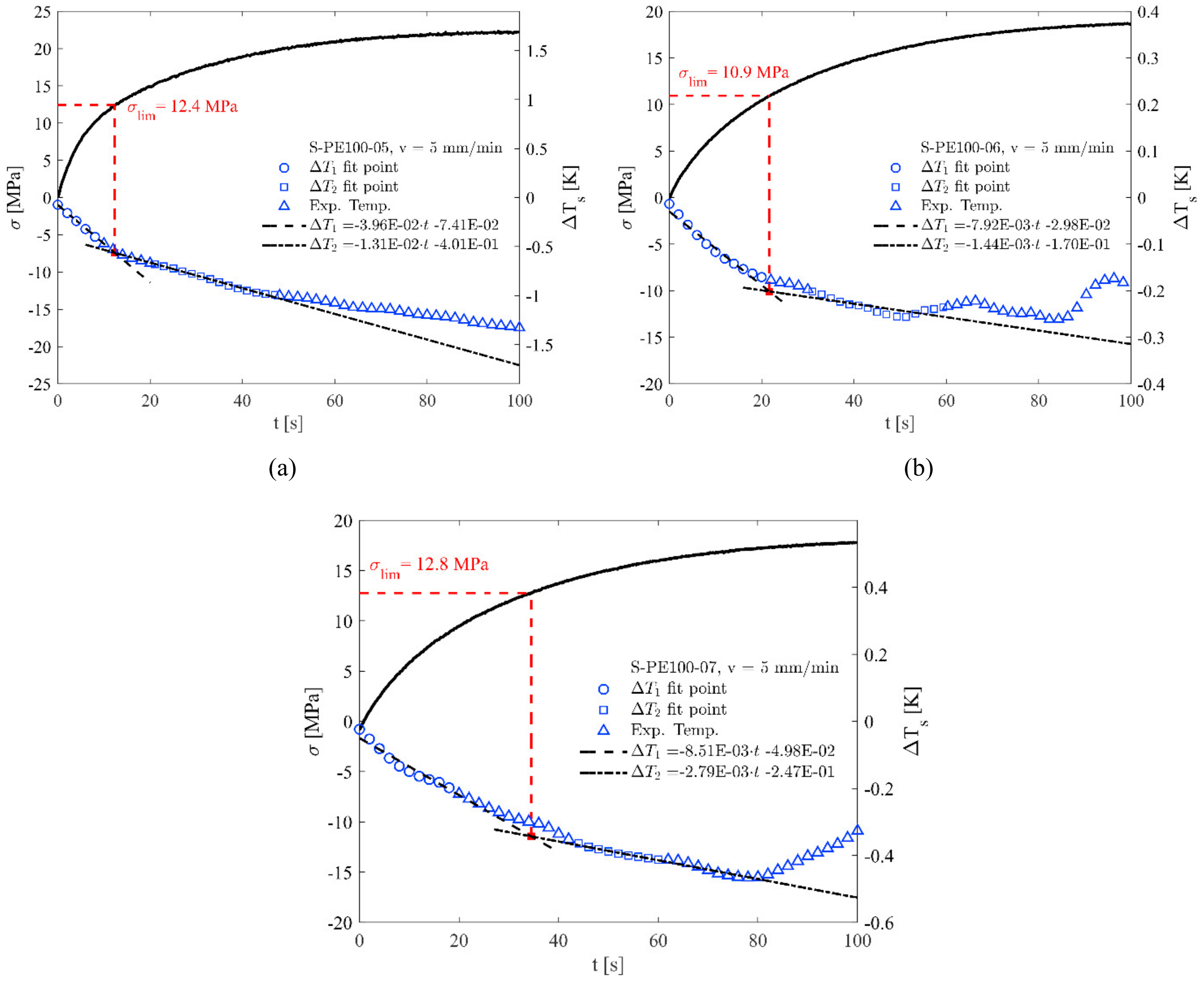
	Tensile Stress at Yield σ_y [MPa]	Tensile Modulus E [MPa]
Authors	23.0±1.1	1036±142
	ISO 527-2 (5 mm/min)	ISO 527-2 (5 mm/min)
Datasheet	25	1100
	ISO 527-2 (50 mm/min)	ISO 527-2 (1 mm/min)

Fatigue tests were carried out with constant stress amplitude, ranging from 12 MPa to 17 MPa, on 8 specimens. A stress ratio of R= 0.1 and a test frequency of 5 Hz were adopted in order to prevent an excessive self-heating of the material. Due to the absence of an evident brittle failure of the specimen, a criterion based on a maximum elongation value was adopted. When the specimen under fatigue load reached an elongation equal to the maximum elastic limit elongation of the material, the specimen was considered failed. The value of the maximum elastic limit elongation was obtained considering the corresponding elastic elongation value of the maximum stress reached by the material during the previous static tests and is equal to 6.9 mm. A number of cycles equal to $1\text{x}10^6$ was considered as the run-out limit for the fatigue tests.

4. Results and discussion

Static traction tests were performed on three PE100 specimens under displacement control, with a crosshead speed of 5 mm/min. The IR camera allows the assessment of the specimen's surface temperature evolution during static tensile tests. The applied stress, evaluated as the ratio between the force and the nominal cross section area of the specimen, is reported versus the superficial temperature variation, estimated as the difference between the instantaneous temperature and the initial temperature of the surface recorded at time zero ($\Delta T = T_i - T_0$) (Fig. 3).

The temperature data has been filtered with a *rlowess* filter, with a data span of 5%, in order to reduce the outliers and highlight the thermoelastic trend. In the initial part of the ΔT-t curve it is possible to clearly distinguish the linear trend of the temperature, then it deviates from the linearity reaching a zero-derivative region, suddenly it experiences a rapid increment. It is possible to make two linear regression lines, 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). An intermediate set of temperature values between the ΔT_1 and ΔT_2 fit point series has not been taken into account in the evaluation of the two regression lines (Experimental Temperature series). Knowing the regression lines equations, it is possible to determine the intersection point of the two straight lines. The corresponding value of the applied stress, namely limit stress $\sigma_{\lim}$, has an average value for the three tests of 12.0±1.0 MPa. It could be related to the macroscopic stress that introduces the first irreversible plasticization phenomena in the material.



(a) (b)

(c)

Fig. 3. Temperature evolution vs. applied stress during static tensile test on PE100 specimens.

A series of fatigue tests has been carried out with constant stress amplitude, ranging from 12 MPa to 17 MPa. In Fig. 4 are reported in a bi-log S-N plot the fatigue test results. Two tests per stress level have been performed, adopting a number of cycle for run out of $N_A = 1x10^6$. The set of data shows an inverse slope k= 7.23 and the fatigue limit with a 50% probability of survival evaluated at N_A is equal to 11.4 MPa. In the same plot is reported the scatter band with one standard deviation for the limit stress assessed by STM.

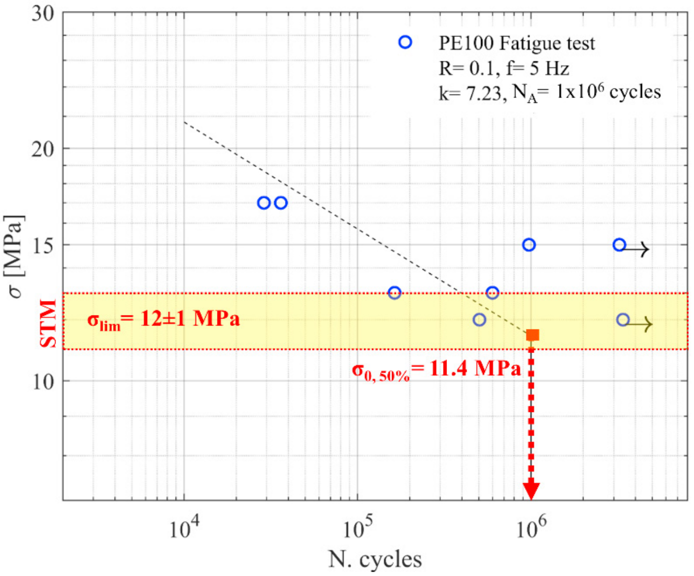


Fig. 4. Comparison between the stress limit and the traditional fatigue tests.

As is possible to note, both failure and run out tests falls within the limit stress scatter band assessed by means of the STM. Also the fatigue limit estimated by traditional fatigue tests falls within the previous scatter band, hence is possible to establish a direct relation between the fatigue limit of the material and the stress limit evaluated adopting the STM. This value, if cyclically applied to the material, will lead to local plasticization phenomena, hence to fatigue failure. The STM could provide a good estimation of the fatigue limit adopting a limited number of specimens and a short amount of time, approximately 5 minutes per test, compared to the traditional fatigue test procedure, which requires a large amount of specimens and a long test time, especially for those materials that cannot be tested at higher frequencies (i.e. plastic and composite materials) due to the self-heating phenomena (Hülsbusch et al., 2019).

5. Conclusion

In this work the energetic release during tensile tests on high-density polyethylene (PE100) specimens has been evaluated. The mechanical properties of the material have been assessed and compared to datasheet values showing good agreement. The IR camera allowed the application of the Static Thermographic Method, monitoring the specimen's surface temperature during static tensile tests. The average value of the limit stress has been evaluated as the stress level at which the temperature deviates from its linear trend, obtaining an average value of 12.0±1.0 MPa on three tests. This value has been compared with traditional fatigue tests showing a direct relation with the fatigue limit of the material with 50% probability of survival (11.4 MPa).

The Static Thermographic Method could be adopted as a fast test procedure able to predict the fatigue properties of the materials from a uniaxial static test in a very short amount of time and with a very limited number of specimens.

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