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Thermal analysis under static and fatigue conditions on HDPE

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Thermal analysis under static and fatigue conditions on HDPE

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Abstract. High Density Polyethylene (HDPE) represents one of the best choices for water and gas distribution pipeline thanks to its light weight and good mechanical performance. One of the strengths of this plastic material is the possibility to join it via welding adopting a procedure according to the standard. However, the welding procedure can severally alter the mechanical performance of the material under service loads. In the present work comparison between virgin and welded HDPE specimens is carried out adopting rapid approaches, such as the Risitano's Thermographic Method and the Static Thermographic Method, monitoring the evolution of the specimen's superficial temperature under static tensile and fatigue tests. Mechanical performance has been compared, as well as the fatigue limit obtained with traditional fatigue tests, showing good agreement. Reliable fatigue data have been obtained in a very short amount of time and with few specimens by adopting Energy Methods.

1. Introduction

High Density Polyethylene (HDPE) is one of the most adopted materials for the realization of pipeline for gas and water distribution. Its strength points are the low cost and light weight if compared to steel pipes. The joining of two different sections of pipe, thanks to their viscoplastic nature, is very easy. Indeed, they can be welded by heating the pipe extremities and applying a pressure for a prescribed time.

In literature, several authors have investigated the mechanical properties of HDPE. In particular, for this kind of material the correlation between the slow crack growth and the chemical composition has been studied [1]. Some authors studied the fatigue properties of HDPE developing damage models [2,3]. To shorten the required test time, Risitano and Santonocito applied infrared thermography to investigate the fatigue life of PE100.

Few studies regarding the mechanical properties of welded HDPE exist in literature. These studies demonstrated how the welding process lead to a restructuring of the crystalline phases, with an increment of the mechanical properties [4–7].

To assess the fatigue properties of welded details compared to the base material, in this work infrared thermography has been applied to specimens of HPDE tested under static tensile and fatigue loading conditions. The Static Thermographic Method (STM) [8] has been applied to identify the limit stress of the material during static tensile tests. It is the macroscopic stress level that causes irreversible damage within the material. The Risitano's Thermographic Method (RTM) [9,10] has been applied to derive the fatigue limit of the HDPE rapidly and with few specimens. Moreover, to verify the findings of the

Thermographic Methods, constant amplitude fatigue tests have been performed on the same specimen's geometry in order to obtain the SN curve and the fatigue limit of the plain and welded HPDE.

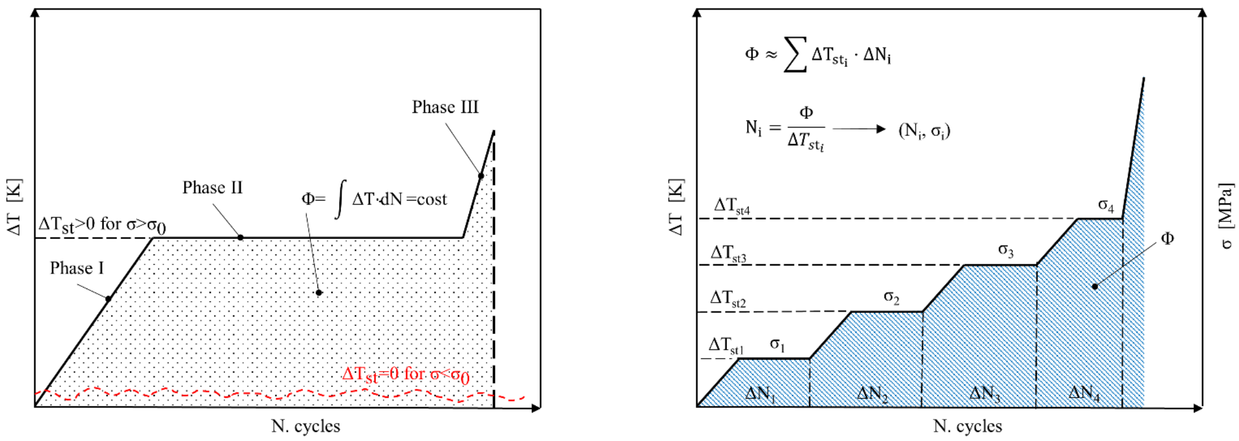
2. Theoretical background

In this section a short overview of the main Thermographic Methods is provided. For more information we remand to specific paper.

2.1. Risitano's Thermographic Method

By observing the temperature evolution of a specimen subjected to cyclic loading condition above its fatigue limit, it is possible to observe three phases [9]. The first phase is characterized by the increment of the temperature. The second phase is characterized by a constant value of the temperature signal in the time domain (Figure 1a). Risitano correlated this temperature value to the onset of fatigue damage within the material. As the applied stress level increase, the stabilization temperature, ΔT_{st}, increase, but the integral of the temperature vs. number of cycles curve remain almost constant. This value, the Energy Parameter Φ, can be related to the dissipated energy of the material.

It is possible to apply on a single specimen, in a stepwise way, a series of stress levels and record the relative stabilization temperatures (Figure 1b). By plotting the stabilization temperatures vs. the applied stress levels, it is possible to recognize the fatigue limit of the material as the knee region of that curve. Exploiting the constancy of the Energy Parameter, it is also possible to rapidly evaluate the SN curve of the material adopting a single specimen. For more information about the Risitano's Thermographic Method we remand to [9,10].



(a) (b)

Figure 1. a) Temperature trend during a constant amplitude fatigue test; b) Temperature trend during a stepwise fatigue test.

2.2. Static Thermographic Method

The main idea of the Static Thermographic Method is to assess the end of the thermoelastic behaviour of a material during a static tensile test.

Risitano and Risitano [8], in 2013, observed how the temperature signal during a static tensile test shows three different phases. Phase I is characterized by a linear decrement of the temperature, due to the thermoelastic law of Lord Kelvin. Phase II is characterized by a temperature decrement but with a different trend compared to the Phase I. At the end of Phase II, the temperature reaches a plateau region, which correspond to the yielding stress of the material. In Phase III, the plastic damage is more predominant compared to the elastic behavior, hence the temperature begins to rise up to the specimen failure.

The transition point between Phase I and Phase II correspond to the onset of irreversible damage within the material. If we are able to assess this point in the temperature signal, we can correlate it to a macroscopic stress, defined as the "limit stress", σ_{lim}, which produces an irreversible energy release due to the increment of plastic damage. For more information about the STM, we remand to [8,11–13].

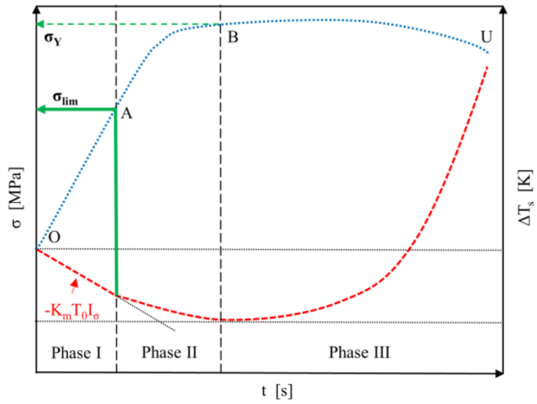


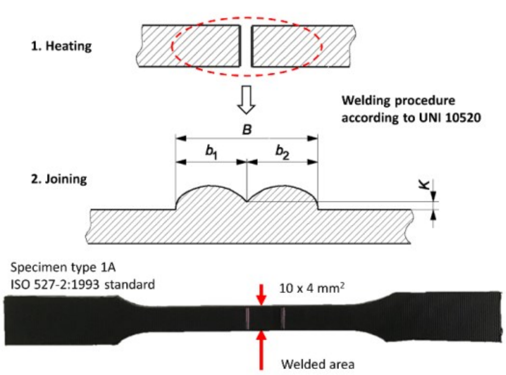
Figure 2. Temperature trend during a static tensile test. Phase I is characterized by a linear decrement due to the thermoelastic constant K_m and the first stress invariant I_σ.

3. Materials and Method

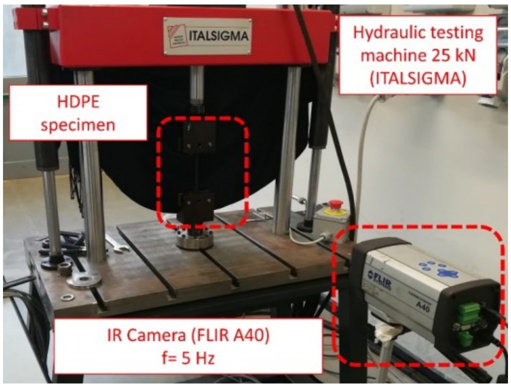
Specimens of HDPE (class PE100, Hostalen CRP 100 Black) were obtained from a pipe section by cutting them according to the ISO 527-2 standard. Two kinds of specimens were tested: the "Plain" one and the "Welded" one. Welded specimens were retrieved from pipe section were the welding procedure, according to the Italian standard UNI 10520, was performed. The welding bead was removed by milling. The nominal cross section of the specimens is equal to 10x4 mm^2.

The specimens were tested adopting a servo hydraulic machine ITALSIGMA 25 kN. Static tensile tests were performed on three specimens per type, adopting a crosshead speed of v= 5 mm/min. Engineering strains were measured adopting an extensometer with an initial gauge length of L_0= 50 mm.

Fatigue tests, both Constant Amplitude (CA) and Stepwise, were performed adopting a stress ratio of R= 0.1 and testing frequency of f= 1Hz, to prevent an excessive self-heating of the specimens. The tests were performed under stress control, starting from 10 MPa up to 17 MPa, with a number of cycles per block equal to 3000. The infrared camera FLIR A40 was adopted to monitor the temperature evolution during the static tensile tests and the fatigue tests. A sampling frequency of 5 Hz was adopted.



(a)



(b)

Figure 3. a) PE100 specimens according to ISO 527-2 standard; b) Experimental setup.

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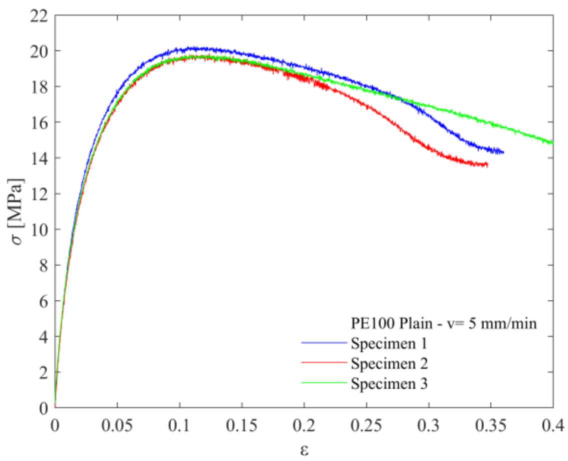
4. Results and discussion

4.1. Static tensile test – Mechanical properties

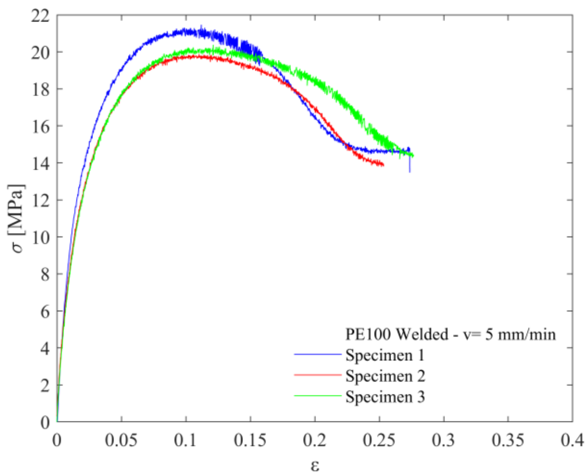
Static tensile tests were performed under displacement control, adopting a speed of 5 mm/min, as prescribed from ISO527-1 standard.

The stress has been evaluated as the ratio between the force and the specimen's cross section. Figure 4 reports the engineering curves of the tested specimens, both plain and welded. The plain PE100 (Figure 4a) exhibits a typical behaviour of plastic materials with a yielding point (i.e. the maximum stress value). After that point, necking begins in the specimen and the stress reduces as the strain increases. For a strain value of $\varepsilon \approx 0.34$, the stress level became almost constant. This stress level is called plastic flow stress.

Welded PE100 (Figure 4b) shows the same behaviour of the plain PE100. The yielding stress is reached for the same stress and strain levels; however, the plastic flow stress has been reached for lower strain values compared to the plain PE100 ($\varepsilon \approx 0.26$).



(a)



(b)

Figure 4. Engineering curve of: a) Plain PE100; b) Welded PE100.

Young's Modulus has been evaluated, according to the ISO527 standard, as the linear regression of the stress vs. strain within the strain levels of $\varepsilon_1 = 0.0005$ e $\varepsilon_2 = 0.0025$. Table 1 reports the value of the Young's Modulus and the yielding stress of PE100. For the plain PE100, average values of E= 1018.9±33.9 MPa and $\sigma_Y = 20.0 \pm 0.3$MPa have been calculated. These values are in good agreement with the manufacturer datasheet (E= 850 MPa and $\sigma_Y = 22$ MPa), even if Young's Modulus is higher. The same considerations apply for the welded PE100 (E= 1155±124 MPa and $\sigma_Y = 20.6 \pm 0.8$ MPa).

There are no excessive deviations of the mechanical properties of welded PE100 compared to the plain PE100, although a greater standard deviation is noticed with respect to it. The values obtained are consistent with the datasheet values of the material as regards the Young's Modulus, while they are slightly lower as regards the yield stress.

The welded PE100 specimens showed the formation of the necking always in areas of the gauge section not included in the zone involved in the welding process, to indicate that the welding zone does not represent a possible site trigger of failure.

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Table 1. Comparison of the mechanical properties of PE100 specimens.

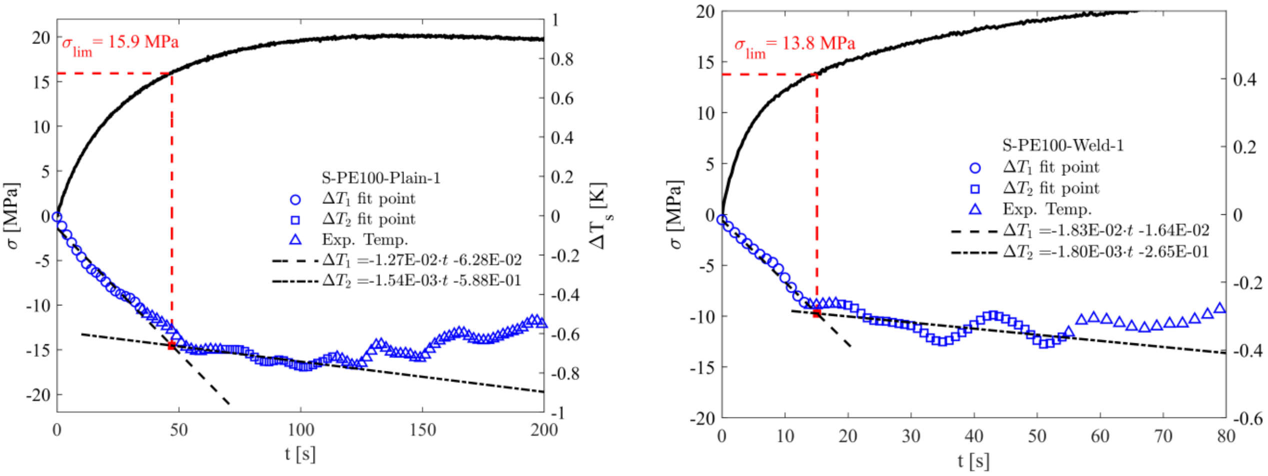
Specimen type	No. Specimen	E [MPa]	σ_y [MPa]	E [MPa]	σ_y[MPa]
PE100 Plain	1	1055	20.3	1019 ± 34	20.0 ± 0.3
	2	1014	19.9		
	3	988	19.8		
PE100 Welded	1	1288	21.5	1155 ± 124	20.6 ± 0.8
	2	1133	19.9		
	3	1044	20.4		

4.2. Static tensile test – Temperature trend

During the static tensile tests, the evolution of the superficial temperature of the specimens has been performed adopting an infrared camera. The temperature of a rectangular spot, placed on the specimen's gauge section, has been monitored and the maximum value has been retrieved and filtered with a *rlowess* filter (data span of 5%). The filter has been adopted to highlight the linear trend of the temperature signal and to remove possible outlier.

The temperature signal has been plotted vs. the applied stress level respect the test time. Figure 5 reports the results for a test performed on plain and welded PE100 specimens. It is possible to distinguish the first linear elastic phase (phase I), followed by a different phase (phase II), where the temperature signal reaches a minimum value and then it begins to increase. By performing the linear regression of the temperature points of phase I (ΔT_1 points) and phase II (ΔT_2 points), and making their intersection, it is possible to assess the limit stress of the material.

For the plain PE100, an average value of σ_{lim}=15.2 MPa has been estimated, while σ_{lim}= 14.2 MPa has been estimated for the welded PE100. Such macroscopic stress level activates in the material some process that lead to irreversible energy release compared to the thermoelastic behaviour, where all the energy is recovered.



(a) (b)

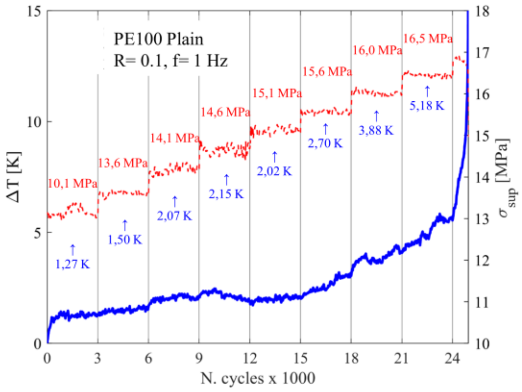
Figure 5. Temperature trend vs. applied stress level during a static tensile test of: a) Plain PE100; b) Welded PE100.

4.3. *Stepwise fatigue test*

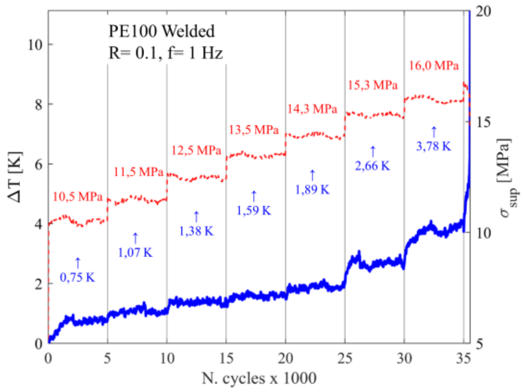
Stepwise fatigue tests have been performed on a specimens per type to assess the fatigue limit with the RTM. The stress ratio has been R= 0.1, while the testing frequency has been set to f= 1 Hz to prevent excessive self-heating of the polyethylene. The superficial temperature signal has been recorded respect the number of cycles and the applied stress level as already done for static tensile tests.

Figure 6 shows the temperature evolution of a stepwise fatigue test, both for plain and welded PE100. At the beginning of the test, the temperature rapidly increases and then stabilizes. It is possible to assess an average value of the temperature signal for the superior applied stress level (σ_{sup}). For the plain PE100 specimen, a further increase of the temperature can be noticed after that 15 MPa stress level has been passed, while, for the welded specimen, it can be noticed after that 14.3 MPa stress level has been passed.

After that these stress levels have been passed, fatigue damage is produced within the material. For lower stress levels, the temperature increments are strictly related to the intrinsic self-heating of the material due to its viscoplastic behaviour.



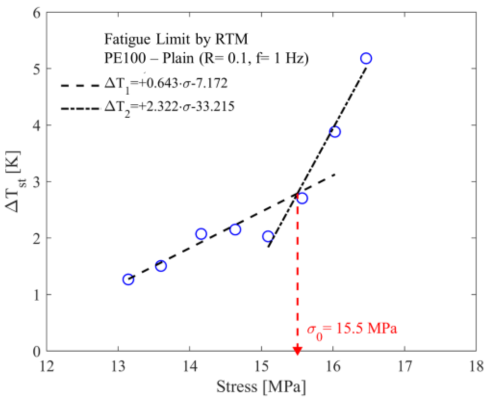
(a)



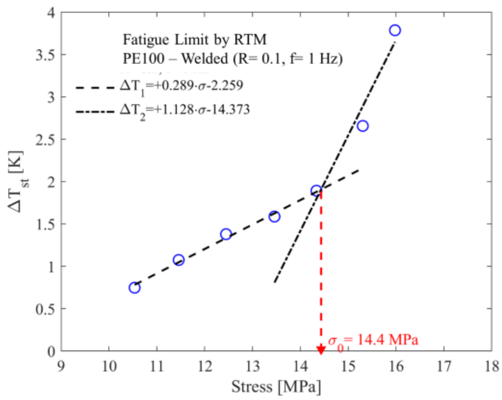
(b)

Figure 6. Stepwise fatigue test of: a) Plain PE100; b) Welded PE100.

By reporting the stabilization temperature vs. the applied stress levels, it is possible to observe a bilinear curve (Figure 7). The first region is characterized by stress levels below the fatigue limit of the material; on the other hand, the second region is characterized by stress levels above the fatigue limit. The knee region is where fatigue damage begins. By performing two linear regressions, it is possible to assess the fatigue limit of the PE100 by RTM. For the plain PE100, a value of 15.5 MPa has been estimated, while 14.4 MPa has been estimated for the welded specimen.



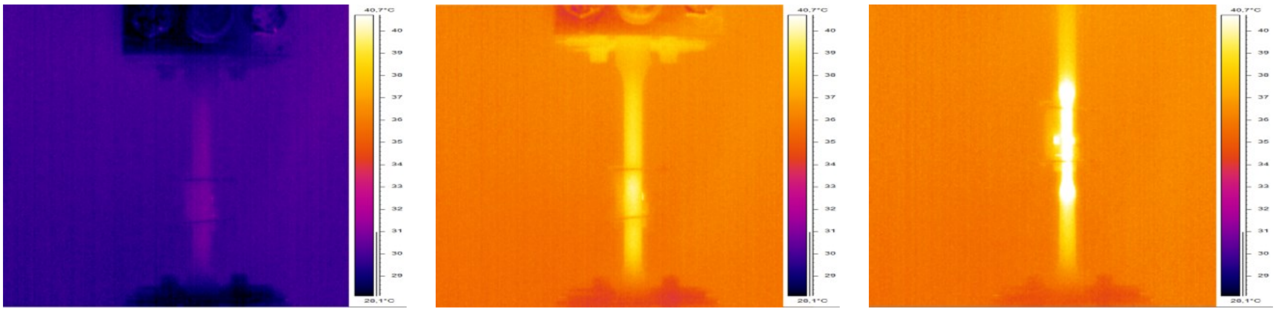
(a)



(b)

Figure 7. Fatigue limit by RTM of: a) Plain PE100; b) Welded PE100.

Figure 8 shows the evolution of the damage in a welded PE100 specimen during the stepwise fatigue test. The extensometer has been placed within the welding zone. In the first frame (Figure 8a) no damage is highlighted by the IR camera, while in the second frame (Figure 8b) a slight temperature increment has been noticed which evolutes up to the specimen's failure (Figure 8c).



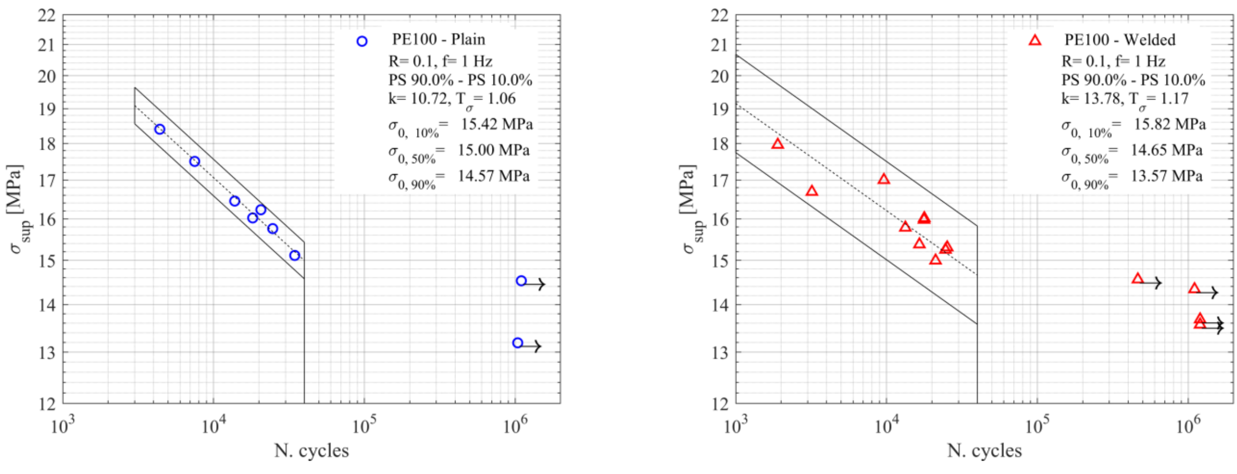
(a) (b) (c)

Figure 8. Damage evolution during a stepwise fatigue test on a welded PE100 specimens. The IR scale is the same for all the frames.

4.4. Constant Amplitude fatigue test

To verify the findings of the Thermographic Methods, a CA fatigue test campaign has been performed on plain and welded PE100 specimens adopting the same stress ratio and test frequency of the stepwise tests. The applied stress levels have been reported vs. the number of cycles to failure in a bi-logarithmic diagram. The scatter band has been estimated with probability of survival (PS) of 10 and 90%, as well as the inverse slope k and the scatter index T_σ. Run-out tests have been considered after that the specimens reaches 1×10^5 cycles without any kind of failure.

The S-N curves of the plain PE100 are shown in Figure 9. It is possible to estimate the inverse slope of this curve by performing a linear regression of the log of the stresses against the log of the number of cycles. For this material type, a value of k= 10.72 has been obtained, while k= 13.78 for the welded PE100. The fatigue limit estimated at 4×10^4 cycles for a probability of survival equal to 50%, is $\sigma_{0,\,50\%}$= 15 MPa for the plain PE100, while it is $\sigma_{0,\,50\%}$= 14.7 MPa for the welded PE100. The other two fatigue limit values, at 10 and 90% of PS, are adopted to estimate the band scatter index ($T_\sigma = \sigma_{0,\,10\%}/\sigma_{0,\,90\%}$).



(a) (b)

Figure 9. S-N curve for: a) Plain PE100; b) Welded PE100.

By observing the graph with the same level of applied stress, welded PE100 has a shorter fatigue life than plain PE100. This phenomenon is particularly evident for higher stress levels. As regards the values of the scatter index T_σ (T_σ= 1.06 for plain and 1.17 for welded specimens), they are consistent with the values typically found in fatigue tests for engineering materials (T_σ = 1 ÷ 1.2).

However, it is therefore possible to observe how the presence of welding has not a detrimental effect on the fatigue limit of the material, but introduces an higher scatter compared to the plain material.

5. Conclusion

In this work, mechanical properties of high density polyethylene have been assessed adopting static tensile and fatigue test. Comparison between plain and welded PE100 has been performed showing how the welding process does not affect the mechanical performances. On the other hand, fatigue damage has shown how the welded PE100 has shorten fatigue life compared to the plain PE100.

To shorten the testing time, rapid energy methods, such as the Static Thermographic Method and the Risitano's Thermographic Method, have been adopted. By monitoring the energy release during a static tensile test or during a stepwise fatigue test, it is possible to severally shorten the testing time, from month to hours, obtaining reliable fatigue information, comparable to time expensive constant amplitude fatigue tests.

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