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ORIGINAL PAPER

Failure behavior of high density polyethylene and high impact polystyrene: An experimental study by damage methods

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ABSTRACT

This work focuses on the damage of two thermoplastic materials; high density polyethylene "(HDPE)" and high impact polystyrene "(HIPS)". The contribution of this work is to determine the lifetime of these polymers by proposing a new static method, including different notches with different opening lengths instead of depth change, to predict the damage behavior of HDPE and HIPS. Three damage models were used to predict the lifetime of these polymers by a proposed simple method compared to the old complex methods. Chemical and microscopic analyses including Fourier transform infrared spectrometry (FTIR) and scanning electron microscopy (SEM) were performed. The results indicated that the shape of the notch and the morphological nature of the polymer influence the mechanical behavior of these polymers. The proposed experimental factors (life fraction as a function of notches) are in very good agreement with the experimental results. **Polyolefins J (2023) 10: 127-136**

Keywords: HDPE; HIPS; models of damage; SEM; FTIR; tensile tests.

INTRODUCTION

Thermoplastic polymers are very usable in everyday life. Thermoplastics are very sensitive to temperature, they become flexible when cold, they soften when heated [1]. High-impact polystyrene and high-density polyethylene, which have different morphologies, are among the best-selling thermoplastics in the industrial field [2]. HDPE and HIPS both have a low cost, they have good impact resistance and high elongation-at-break [3]. HIPS has smaller tensile strength and elastic modulus compared to unreinforced polystyrene [4], on the other hand HDPE has a semi-crystalline morphology. HDPE is usually obtained by the polymerization of ethylene and is part of the family of polyethylene [5], with great strength, ductility, durability and lightness [6]. HIPS due to its high impact is known in the field of packaging and electrical instruments. The ductility of HDPE has caused 43 million tons of this material to be produced annually [7]. HDPE is the most widely used material in the pipe industry [8]. Several studies have been conducted to characterize the mechanical behavior of polymers. Hu

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et al. [9-10] determined the fatigue crack prevention in order to calculate the minimum levels of pre-stressing of CFRP polymer through experimental and numerical study under pressure fatigue of CFRP-reinforced concrete. Ouman studied the properties of PVC cable under the static damage [11].

The fatigue behaviour of HDPE pipes has been analyzed by several authors using several damage models in order to finish the durability of these pipes [12-19]. Ouardi et al. compared PPR and HDPE pipes [20], and comparison between HDPE and CPVC pipes was made by another work [21]. The research method for HIPS is different from that of HDPE. Francisco determined the life cycle of HPIS using thermo-oxidation [22]. Characterization by J-integral methods to establish the fracture strength at different thicknesses with cracks indicated that the experimental hysteresis method, capable to determine the nature of the crack, which is either blunt or non-blunt [23]. Hanane et al. appreciated the fracture behaviour of HIPS used in disposable cups, subjected to several recycling cycles [3].

The cyclic behavior of HDPE and HIPS can be considered, but in this work, a new approach based on static tests was performed to evaluate the damage of HDPE and HIPS plates through two categories of notches, which are U flat bottom and V to make a simulation with fatigue tests. These artificial notches with constant depth and opening length ranging from 5 mm to 90 mm were created to evaluate their effects on the damage evolution and mechanical response of HDPE and HIPS. In the first part, the methodology of the experimental tests as well as the procedure of cutting and obtaining the specimens for HDPE and HIPS were described, and the chemical properties of each polymer were analyzed by Fourier transform infrared spectrometry (FTIR). In addition, the surface faces of the notched specimens were observed by scanning electron microscopy (SEM), and the results of the tests are represented in terms of damage evolution as a function of the life fraction in the last part. The results showed that the shape of the notch has an influence on the mechanical behavior of the studied thermoplastics, and their morphology that are either amorphous or semi-crystalline. The critical life fractions for each type of notch and each polymer were targeted by measuring and comparing the damage. Damage evolution evaluated by the modified unified theory is not dependent on the material and conditions used.

EXPERIMENTAL

Preparation of the samples

The characterization specimens (Figure 1) and notched specimens were obtained from HDPE 100 plates of dimension (300 mm × 210 mm × 1.1 mm) and HIPS plates of dimension (300 mm × 300 mm × 1 mm). U and V notches were made on HDPE and HIPS specimens using a saw cut, followed by a sharpening with a razor blade for good accuracy. The specimens have the same notch depth of 5mm for both materials, and the openings of defects varied from 5 mm to 90 mm. For each defect opening length (either U or V), four sets of tests (four specimens) were performed.

Characterization of materials

For the experimental procedure, first of all, HDPE and HIPS were characterized using dumbbell specimens to determine their pristine mechanical behavior and mechanical characteristics such as Young's modulus, ultimate stress and stress-at-break. For each polymer, three specimens were tested, and the characterization curves (stress-strain) obtained are presented in Figures 5 and 6.

The mechanical fatigue behavior of polymers can be assimilated by static tests. The effect of change of opening is similar to the effect of change of notch depth. For this, tensile tests were performed on U- and V-notched specimens (Figure2-3) to calculate damage patterns (Eqs 1-4), life fraction (β), damage mechanisms, and to assimilate the controlled pre-loading as ultimate residual stress (σ_{ur}) and stress just before failure (σ_a).

The HIPS and HDPE specimens contain notches of the same depth with different opening lengths (from 5 mm to 90 mm).

The tests were performed in a universal MTS series 40 machine with a load capacity of 5kN, that the machine was controlled by a MTS TEST SUITE software, which gave the results as force-displacement.

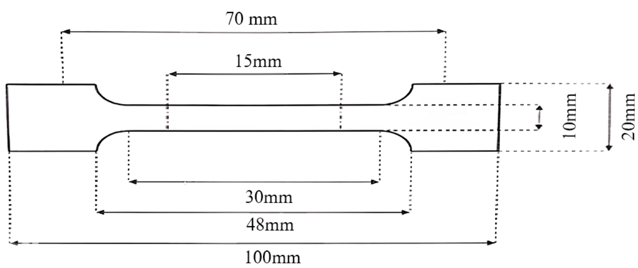


Figure 1. Dimensions of the HDPE and HIPS specimens used for the characterization.

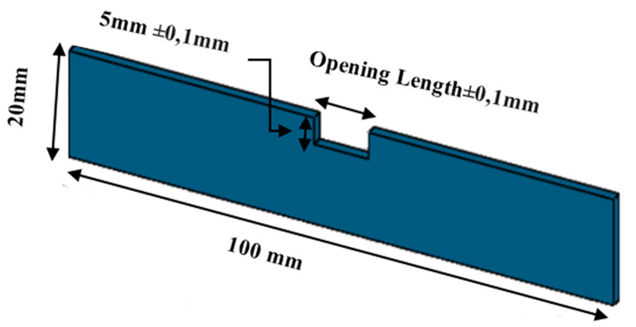


Figure 2. Dimensions used for HIPS and HDPE U-notched specimens.

FTIR and SEM characterization

A SHIMADZU-IRAffinity-1S transmission FTIR instrument was used in this work. This device allowed light to pass through thin HDPE and HIPS samples. Transmission mode Fourier transform infrared spectrometry was used to determine chemical compositions of HDPE and HIPS to highlight the difference between the two polymers between 900 cm^{-1} and 1700 cm^{-1}.

The morphology of HDPE and HIPS surfaces was studied by SEM (SH 4000M) (Fsac, Morocco).

Figure 4 represents the absorbance of HDPE and HIPS as a function of wavenumber. In this figure a shift in peaks can be observed between the two polymers exploiting the morphology, and polymerization mode of each material. For HDPE, the chemical double bond peaks of type ($C=CH_2$) at a wavenumber of 929 cm^{-1} and C=C at 1510 cm^{-1} describe the method of polymerization of HDPE by ionization of ethylene. For HIPS, the peak at 1610 cm^{-1} belongs to the hinge bond of type C-H that introduces the polymerization of polystyrene in the presence of butadiene that gives the amorphous morphology of strong impact.

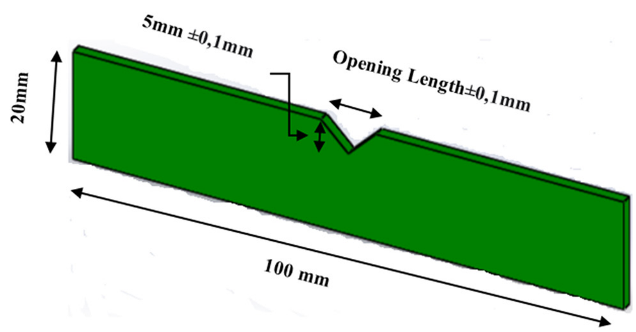


Figure 3. Dimensions used for HIPS and HDPE V-notched specimens.

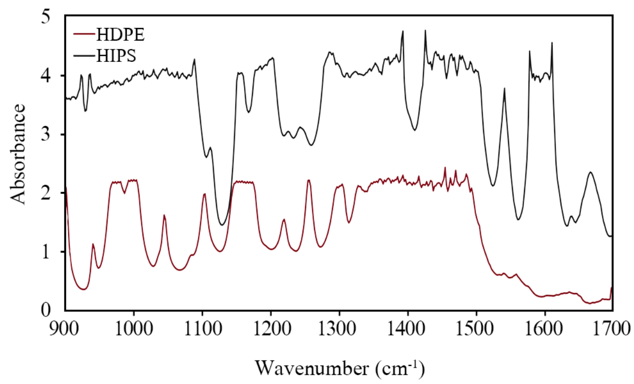


Figure 4. HDPE and HIPS IR spectrometry.

RESULTS AND DISCUSSION

Characterization of the mechanical behavior of HIPS and HDPE

The force-displacement curves obtained from the application of tensile tests on HDPE and HIPS weighted characterization specimens (Figure 2) were transformed to stress-strain curves (Figure 5,6), by dividing the force on the surface of the specimen, and the displacement by the initial length of the specimen. It can be noticed that the stress-strain curve of HIPS represents a ductile behavior divided into two zones. A viscoelastic zone where the stress continues to increase with the increase of the deformation until reaching the elastic limit of value 35 Mpa. From 12% of deformation to 30%, the stabilization of the stresses was noted, where the stricture of the material begins. HIPS was characterized by an important viscoplastic plateau. It is noted that HIPS has a high tensile strength and deformation-at-break.

The behavior of HDPE differs (Figure 6), and the most important remark is that the deformations are very low, the elastic part where the material can regain its initial shape if the loading is stopped, starts from 0 to 12 MPa, since the material is amorphous so at 10% strain the yield point appears, and a decrease in stress

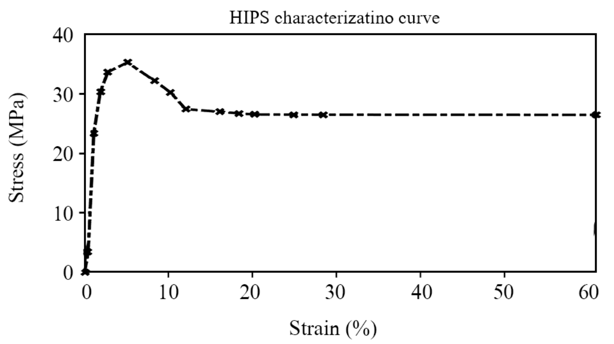


Figure 5. HIPS characterization curve.

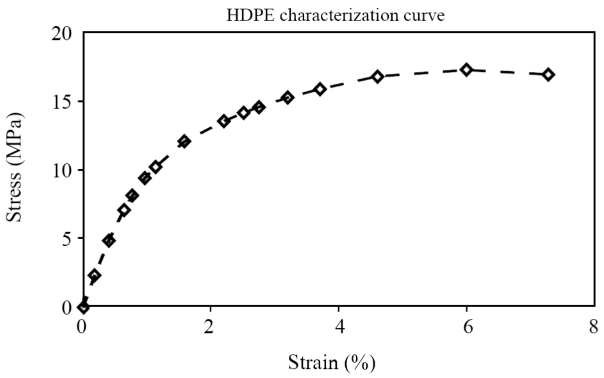


Figure 6. HDPE characterization curve.

was observed. The initiation of the plastic part that leads to the stricture of the specimen is 12MPa until the failure of the material, in this case low ductility and tensile strength were observed for HDPE.

Damage methods for notched HIPS and HDPE

Damage mechanics in the theoretical basis is the analysis of progressive damage of polymers and materials. Based on the concept that the material can bear other loads after the damage occurs, this analysis respects the concept of three principles: the relationship between damage and stress field, the criterion of strength of materials and the relationship between deformation and stress field. Therefore, the damage analysis is based on several theories, the most known theory is the CDM (CONTINUOUS DAMAGE MECHANICS). This theory describes that the damage of polymers as an internal variable is incorporated in an irreversible thermodynamic process.

The polymer fatigue model and the ductile damage model work are based on the theory of CDM. Several works have been established on the fatigue damage models of polymer materials [24-28], but these fatigue damage models are not applicable for HDPE and HIPS directly, since dynamic fatigue tests are expensive and slow. Therefore, we replace these fatigue tests and endurance stresses by the evolution of defects, strength and stiffness to adopt the models of unified theory damage, static damage and modified unified theory damage, because these three models are based on CDM [29]. The damage models used gave us an evolution of the damage as a function of the life fraction and allowed us to approximate the dynamic damage obtained from the fatigue test.

The linear damage or Miner damage [30] is given by:

$$D_M = \sum_{i=1}^{M} \frac{n_i}{N_i} \qquad (1)$$

n_i: The applied number of cycles.
N_i: The fatigue life.
M: The number of applied fatigue load.
The static damage [31] is:

$$D_s = 1 - \frac{\sigma_{eff}}{\sigma} \qquad (2)$$

σ_{eff}: The effective stress.
σ: The ultimate strength of material studied.

The unified theory evaluates cumulative damage by fatiguing HDPE and HIPS thermoplastics and running static tensile tests to failure. When the opening length of each U and V defect varies from 5mm to 90mm, the number of cycles consumed per fatigue test is high.

The damage per unified theory according to [18] is:

$$D_u = \frac{\beta}{\beta + (1-\beta)\left[\dfrac{\dfrac{\sigma_{ur}}{\sigma_a} - \left(\dfrac{\sigma_{ur}}{\sigma_u}\right)^m}{\dfrac{\sigma_{ur}}{\sigma_a} - 1}\right]} \qquad (3)$$

σ_{ur}: The ultimate residual stress for damaged U and V specimens.
σ_u: The ultimate stress value in the virgin specimens of HDPE and HIPS.
σ_a: The value of stress just before failure.
β: Life fraction, in our case is the ration between the opening length for each type of notch and total length of the specimens.
m: Polymer material parameter.

The damage model of the modified unified theory is a model for defect geometries such as U defect and V defect [13], it is a similar model to Miner's model. The S parameter in our case is 1 for the U defect and 1.5 for the V defect, and these models are applicable to both polymers in our study.

$$D_{uM} = \frac{\beta}{\beta + ((1-\beta)\left(\frac{\sigma_u}{\sigma_{ur}}\right)^2)} \qquad (4)$$

the stress-strain curves were obtained by the application of tensile tests on the U and V notched specimens (Figures 2-3).

The results obtained from the calculation of the three damage models are shown in Figures 7-14. The objective of the comparison of the curves (Figures 7-14) is to show the harmfulness of the type of notch and the morphology of the material on the calculations of the damage, thus the difference between the three

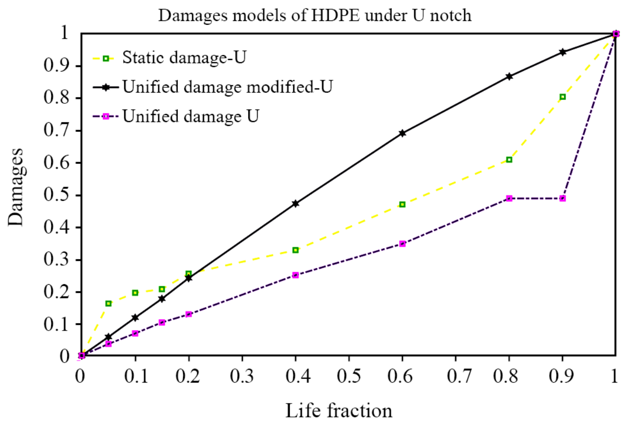


Figure 7. Damage patterns of U-notched HDPE.

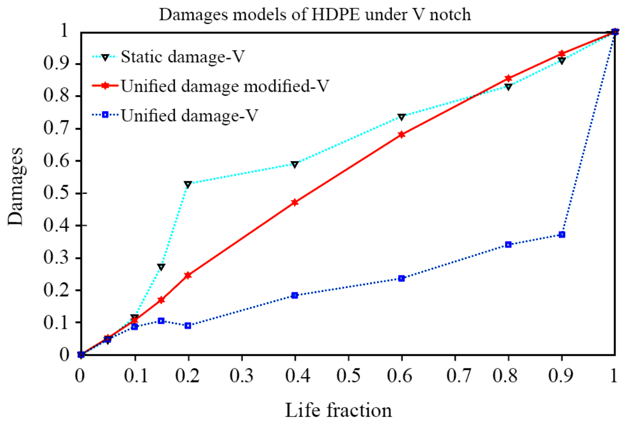


Figure 8. Damage patterns of V-notched HDPE.

calculated damages.

From the experimental results of static damage (Figures 7-14), three phases for HDPE and HIPS were noticed:

-Phase 1: is characterized by a slow evolution until the first critical life fraction 0.2 for different defects and different polymers.

-Phase 2: is characterized by a steady increase in static damage up to a second critical life fraction of value 0.9.

-Phase 3: is characterized by a significant acceleration of the damage D_u and D_s (Eqs 2-3) until reaching the unit.

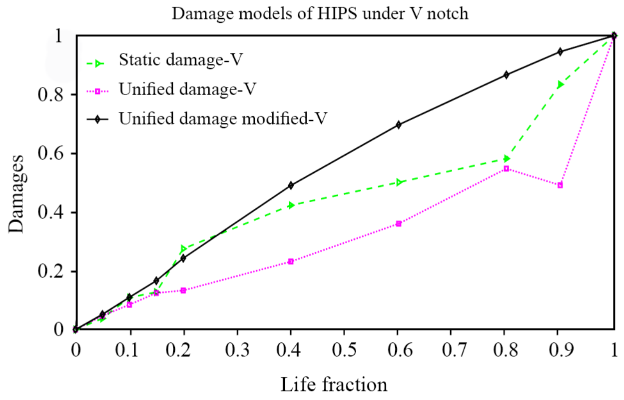


Figure 10. Three damage models calculated for V-notched HIPS.

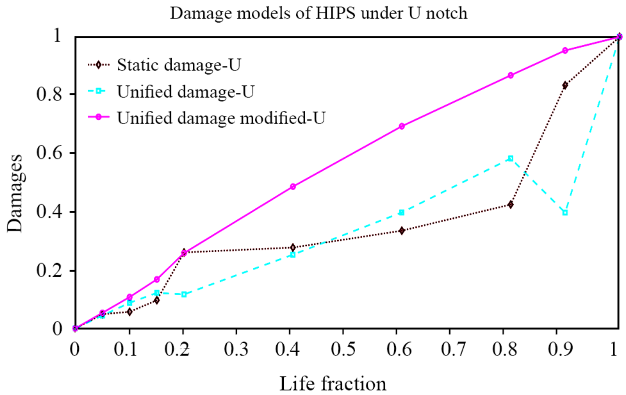


Figure 11. Three damage models calculated for U-notched HIPS.

These three phases obtained are consistent with the results of studies done on HDPE pipes, where

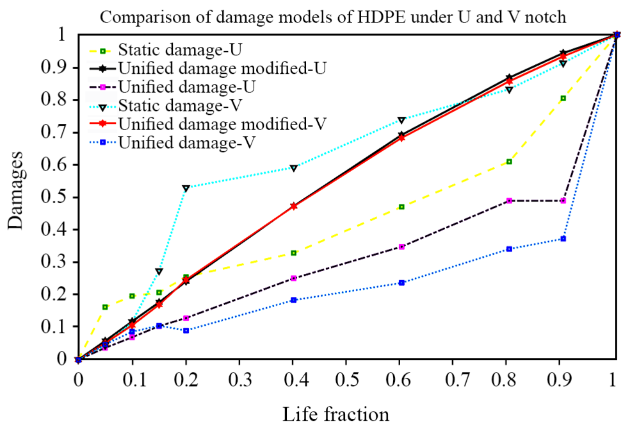


Figure 9. Comparison of damage in the U and V-notched HDPE.

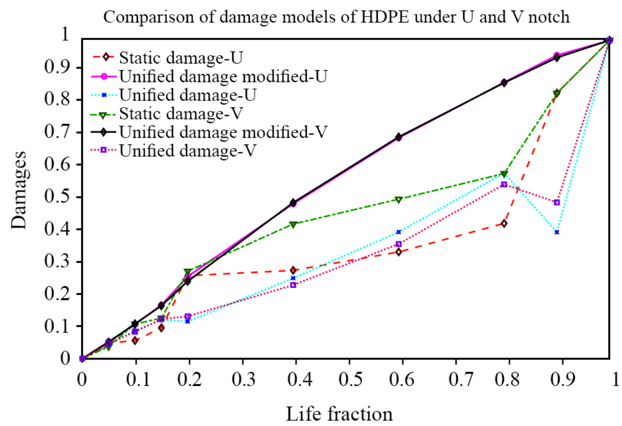


Figure12. Damage comparison of U and V-notched HIPS.

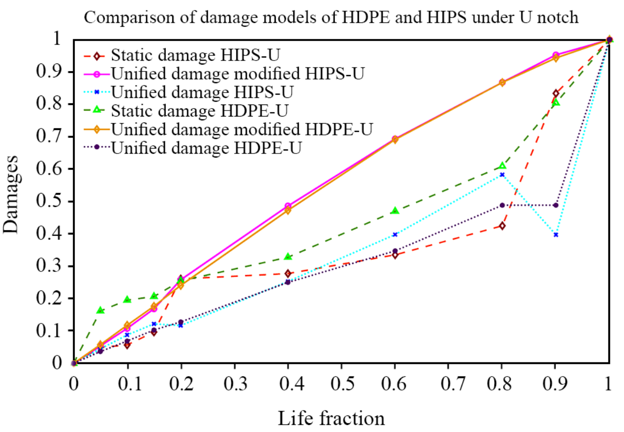


Figure 13. Damage comparisons of HIPS and U-notched HDPE.

the damage by CDM also divides into three phases with two critical life fractions 17% and 65% [8], in this regard, in the same study done by the energetic damage, three phases of the damage of HDPE were found with a critical life fraction of 25% and 52% [31-34]. So, the occurrence of the three damage phases for HDPE and HIPS is an analysis that varies depending on the critical life fraction, and the type of tests and polymer.

Comparison of the impacts of faults U and V (Figures 9 and 12) shows the following results:

- The damage values of defect V are always large compared to the damage values of defect U for the damage model by unified and static theory.
- The U defect has a higher impact than the V defect, for the two thermoplastics studied, which means that the V defect has more weakening of strength and ductility compared to U, and the V defect is more dangerous.

These results of comparison of the impacts of the two notches is a confirmation and extension of the

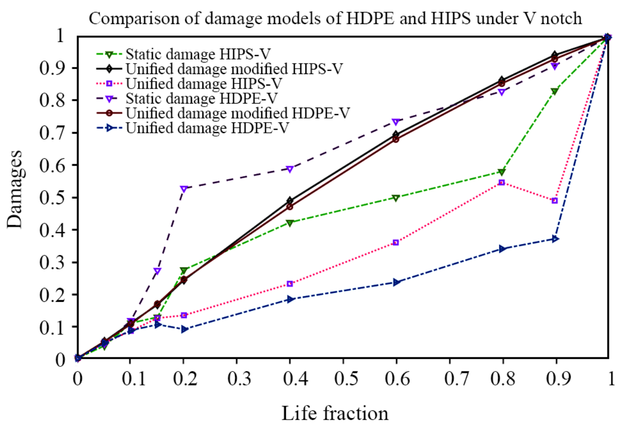


Figure14. Damage comparisons of HIPS and V-notched HDPE.

later work done by Zheng et al. [13], where the burst pressure decreases with the depth ratio, which it is the same for our case, so the residual ultimate stress decreases with the increase of the opening length ratio. The use of the modified unified theory damage model (Figures 7-14) has some limitations:

- The modified unified theory damage does not depend on the type of defect geometry, characteristics and structural morphology (semi-crystalline or amorphous).
- The evolution of D_{uM} is invariant to the life fraction.
- The maximum stress is independent of the theoretical equation of D_{uM} (Eq. 4).

Figures 7, 8, 10 and 11 show that the static and unified theory damage becomes more and more non-linear with increasing defect opening length. Comparison of the curves between the two polymers (Figurs 13-14) shows that HIPS is more resistant to defects than HDPE, because the static damage values for the U and V defects are lower than the static damage values for HDPE, in fact the presence of butadiene in HIPS leads to high stiffness and ductile fracture, whereas HDPE has brittle fracture and brittle behavior, i.e., a drastic drop in stress-at-break. The results of Ouardi et al. agree with our study, since the morphology of PPR and HDPE differs [20], and also the performance of the two materials is not the same when comparing the damage with two values of critical life fraction, 32% and 75%.

Mechanical characterization by SEM of HDPE and HIPS under notches

After analyzing the fracture surfaces of HDPE and HIPS by SEM, the following results were obtained. The analysis of Figure 16 allowed us to observe the micro-mechanisms due to the growth of the pre-crack in relation to the geometry of the defect, so we can note that the presence of fibrils in Figure 15b describes the step that follows the crack propagation, which can be generated cavities that are visible due to the high concentration of stress at the level of the defect V. It can be noticed for Figure 15d that the generation of fibrils induces a remarkable plastic deformation. The photographs of HDPE in SEM show that the pre-cracking increases if we change the type of the defect to give a groove. The increase of the angle of notch V and the length of opening lead to a brittle rupture of the HDPE material. After examining the HIPS images (Figure 16), it is evident that the length of crack propagation of the V defect (Figure 16b) is greater than that for the U defect (Figure 16d). The lines of

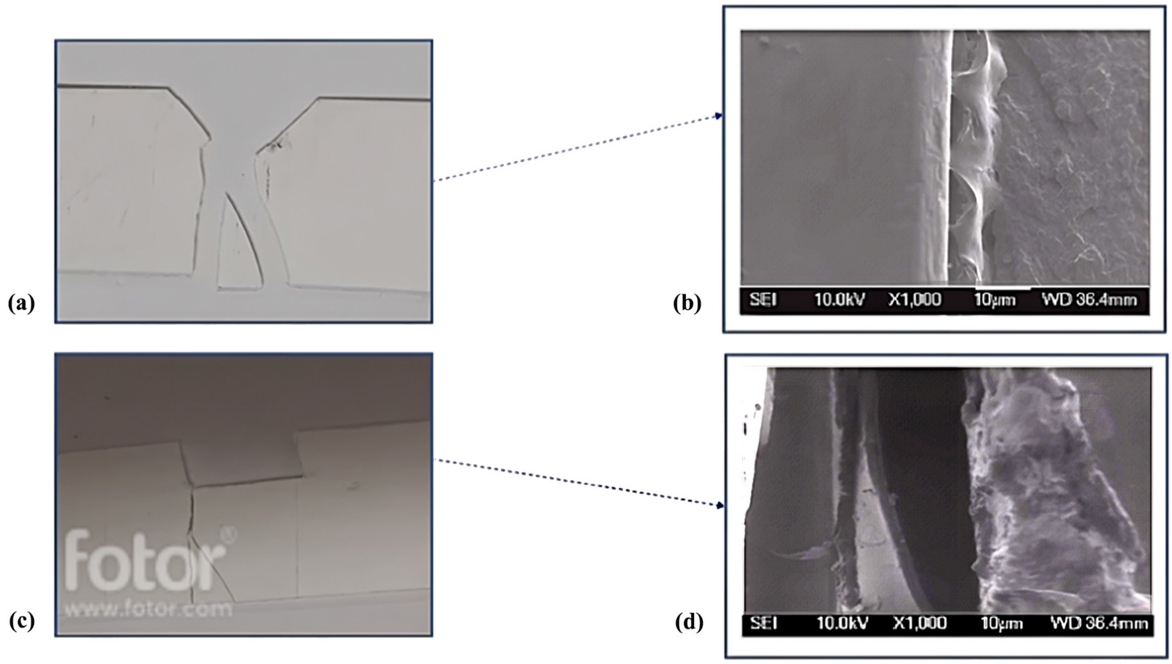
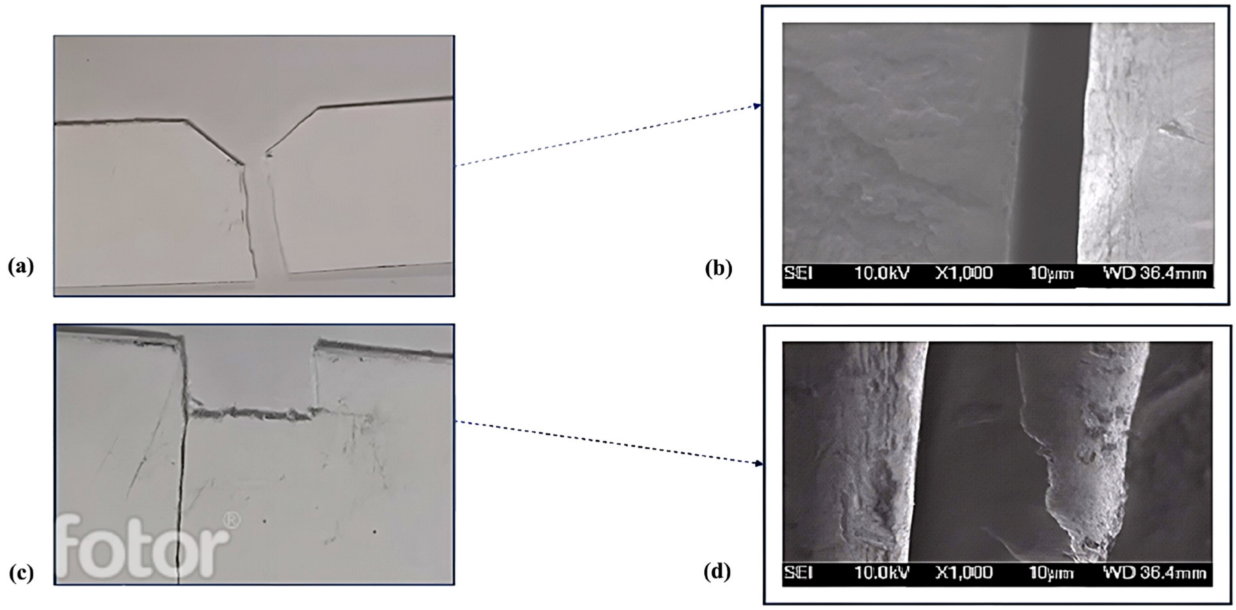


Figure 15. Image results for HDPE: (a): HDPE with V-notch, (b): V-notch SEM, (c): HDPE with U-notch, (d): U-notch SEM.

propagation are visible because of the close contact with the defect groove, and the plastic deformation traces are higher at the V defect and the amount of crack propagation that enters the PS matrix is greater, and the number of butadiene spheres in the U defect image is limited. With a comparison between the two polymers, the micrograph shows that HIPS is more resistant to defects, as the deformation of the butadiene spheres is where the crack bottom stops, allowing HIPS to resist the formation of additional cracks. The brittle fracture morphology of HDPE is clearly indicated by the low plastic strain in the sample section region compared to the plastic strain of HIPS. These results are in agreement with the results obtained from static damage and unified theory (Figurs 7-14). Both polymers were influenced by the defects that significantly reduced the ductility, stiffness and strength.



Figures 16. Image results for HIPS: (a) HIPS with V-notch, (b) V-notch SEM, (c) HIPS with U-notch, (d) U-notch SEM.

CONCLUSION

In this paper, a comparison of the damage behavior of high-density polyethylene and high impact polystyrene under the effect of defects was made, and three damage models were calculated using residual stresses and ultimate residual stresses that replace tenacities and strengths. In this regard, both thermoplastics showed a similar damage tendency, that is, HDPE has a low ductility compared to HIPS, which maintains its ductile fracture. The results were confirmed by the microscopic analysis of the SEM images of the fracture surfaces of these polymers, and a non-linearity of the damage by the unified theory and the static damage was represented when the opening length increased and this is the case for the two defects and the two polymers. The comparison of the damage by unified theory modified for HIPS and HDPE for the different defects revealed that D_{uM} is not influenced by the nature of the polymer morphology and the type of notch with a damage similar to Miner's damage. The V defect affects the weakening of the material more than the U defect. Future work will focus on numerical validation by a simulation software of all the concepts presented in this paper, which will be an experimental study by other aspects like accelerated aging and comparison of notches and the application of the concepts presented on other materials with ductile behavior.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

NOMENCLATURE

n_i: The applied number of cycle
N_i: The fatigue life
M: The number of applied fatigue load
σ_{eff}: is the effective stress
σ: The ultimate strength of material studied
σ_{ur}: The ultimate residual stress for damaged U and V specimens
σ_u: The ultimate stress value in the virgin specimens of HDPE and HIPS
σ_a: The value of stress just before failure
m: Polymer materials parameter

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