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EFFECT OF STRESS-FREQUENCY INTERACTION ON THE FATIGUE BEHAVIOUR OF HDPE MATERIAL

UTICAJ INTERAKCIJE FREKVENCIJE NAPONA NA PONAŠANJE ZAMORA HDPE MATERIJALA

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Keywords
- fatigue,
- cyclic behaviour
- frequency
- stress amplitude
- dissipated energy
- high density polyethylene (HDPE)

Abstract

In this experimental study, the influence of test frequency and applied stress on the evolution of dissipated energy and number of cycles is studied. This made it possible to optimise these parameters to achieve a long service life by minimizing the dissipated energy while maximizing the frequency of the test. An experimental design is used to establish and validate a predictive model of energy and the corresponding number of cycles using response surface methodology (RSM). Two inputs, namely frequency and applied stress are considered as input parameters, and number of cycles and dissipated energy are treated as the outputs. For this, an analysis of charge-discharge loops is carried out and the values of dissipated energy included in these loops are determined. Based on these energies obtained for different stress amplitudes and frequencies, mathematical models have been proposed which estimate the corresponding number of cycles as well as the dissipated energy. Thus, it has been shown that the parameters most influencing the cyclic behaviour of the studied HDPE are in order: the stress amplitude and frequency. The interaction study made it possible to find combinations of these factors for a given number of cycles.

Ključne reči
- zamor
- ciklično ponašanje
- frekvencija
- amplituda napona
- gubici energije
- polietilen visoke gustine (HDPE)

Izvod

U ovom eksperimentalnom istraživanju proučava se uticaj ispitne frekvencije i primenjenog napona na razvoj gubitka energije i broj ciklusa. To je omogućilo optimizaciju ovih parametara kako bi se postigao dug vek minimiziranjem rasipane energije uz istovremeno povećanje frekvencije ispitivanja. Korišćen je projektovani eksperiment za uspostavljanje i potvrdu modela predviđanja energije i odgovarajućeg broja ciklusa korišćenjem metodologije površine odziva (RSM). Dva ulaza, naime frekvencija i primenjeni napon se smatraju ulaznim parametrima, a broj ciklusa i gubitak energija se smatraju kao izlaz. Za tu svrhu je izvedena analiza petlji opterećenja-rasterećenja i određene su vrednosti rasipane energije uključene u tim petljama. Na osnovu ovih energija dobijenih za različite amplitude i frekvencije napona, predloženi su matematički modeli koji procenjuju odgovarajući broj ciklusa kao i gubitke energije. Dakle, pokazalo se da su parametri koji najviše utiču na ciklično ponašanje proučavanog HDPE materijala redom: amplituda i frekvencija napona. Studija interakcije omogućuje iznalaženje kombinacije ovih faktora za zadati broj ciklusa.

INTRODUCTION

In recent years, the use of polymers in various engineering applications has increased, which is why more and more attention is devoted to their performance and behaviour under cyclic loading conditions. Consequently, a great request for data necessary for design calculations (engineering) including forecasting lifetimes is generated.

On a macroscopic scale, the behaviour under cyclic loads of polymeric materials has in common with that of metals a decrease in stiffness during the loading /1/. In the case of metals, this phenomenon comes from the progressive development of micro-plasticity then from damage. In the case of polymers, whose behaviour is intrinsically viscous, the drop in stiffness can also come from the viscoelastic part of the response.

Metals are generally tested at a frequency which presents no obstacle to the application of data over a wide range of frequencies when the material is elastic /2, 3/. A first difference is that the polymers will exhibit greater sensitivity to the test frequency, /4/. A second one concerns the principle of fatigue design. Indeed, such an extrapolation in metals is based on the nature of the ruin mechanisms /5-7/, of mainly mechanical origin. In polymers, on the other hand, the viscous nature of behaviour questions the definition and simulation of this stabilized state according to the stress conditions. For the same reasons, temperature sensitivity will also be greater. Lesser distinguished are the different fatigue failure regimes /8/. Among others, a low cycle fatigue regime associated with significant heating and ductile failure, /9/. The heat produced during fatigue loading in each cycle is too great. For semi-crystalline polymers such as high-density polyethylene (HDPE), it has been shown that thermal fatigue failure generally occurs with high stress /10-14/, high deformation /15/, or at high frequency /14, 16, 17/. However, polymers dissipate heat due to the inherent damping of the material, which manifests itself in their hysteresis curve during cyclic loads. Warming up significantly reduces fatigue behaviour.

The regime is characterized by high resistance to fatigue under a low level of stress. Most often, the rupture observed is of a fragile nature, and there is low energy dissipation in the hysteresis loops, which indicates that the applied load has no significant effect on the temperature of the sample /8, 18, 19/. This regime is also called the domain of ‘mechanically-dominated’ fatigue. Numerous studies have established a link with the evolution of viscoelastic properties /8, 18-20/. Between these two regimes, there is a transition phase of a few tens of cycles, /17-25/.

For many polymers subject to cyclic stresses, only cyclic softening is observed, even if the extent of this softening depends on the structure of the polymer /26, 27/. In this context, an example of the cyclic softening phenomenon is given by Djebli and co-authors for an HDPE /28/. Indeed, it is reports that when constant cyclic stress amplitude is applied, there is a first step where a strain peak is reached and kept almost constant with a slight linear increase, then a transition step where the strain increases with the cycles. In addition, several other studies have studied the kinematics of hysteresis loops during stress-driven fatigue tests /29-32/. They mention the displacement of the charge-discharge loops towards higher deformations during the life of the specimen.

In general, the cyclic softening phenomenon is not observed for all polymers. In polystyrene (PS), this phenomenon is little observed, since fatigue tests with controlled deformation, or with controlled stress at a frequency of 0.1 Hz gave practically the same Wöhler curve, /33/. Knowing the harmful effect of the stress amplitude on the lifetime of a polymer, some works show that the shape of the signal has a significant effect on this lifetime. Crawford et al. /12/ have shown, in uniaxial compression that a square waveform is more penalizing than a sinusoidal waveform, mainly in the limited endurance zone. They attributed this effect to greater energy dissipation. This result was extended in uniaxial traction by Janssen et al. /34/ on several thermoplastics (PC, PMMA, HDPE, iPP). This, without omitting influence of the test frequency of which essentially depends on the viscoelastic nature of the polymer. Thus, where hysteretic loop is significant, the increase in frequency would certainly cause an increase in the dissipation of energy, /35/. As a result, a considerable increase in temperature will be caused and will affect the fatigue life of the material studied. Paradoxically, under appropriate conditions, by increasing the frequency, one sees the lifetime increase. One reason for this phenomenon is that a high frequency implies a high strain rate and therefore it will generate a high elastic modulus and the same for the yield limit of the material /36, 37/. Indeed, it is reported in /36/ that HDPE fatigue life slightly varies between 0.2 and 2 Hz. On the other hand, at higher or lower frequencies, the life of the test specimen decreases sharply. However, according to the author, the origin of this decrease in a lifetime does not seem to be the same in the two situations.

Mainly, the objective of this work is to analyse experimentally, the interaction effects of stress, and frequency of the test on the extent of the dissipated energies in each loading cycle. By this, the final objective is to optimise the choice of fatigue test parameters such as stress and frequency and propose a mathematical model predicting hysteretic (dissipated) energies.

MATERIAL AND EXPERIMENTAL METHOD

The objective of this experimental study is the mechanical characterization of HDPE. The test protocol is carried out in two parts. The first part concerns tensile tests to statically characterize the studied material. The second part concerns cyclic tests to determine the fatigue behaviour of our HDPE subjected to a cyclic tensile loading.

The aim of this second part of the tests is to analyse the interaction effect of the frequency and the stress amplitude on the energy dissipation during the loading cycles. Then, by the curves obtained from the energies as a function of the cycles, a model will be proposed which predicts, by this interaction, the dissipated energy.

The material of this study is the same as that studied by Djebli et al. /37/. A section of HDPE pipe was supplied by CHIALI STPM. Thus the tensile and fatigue test pieces are taken by cutting the pipe and then machined by milling to obtain the shapes indicated in Fig. 1. The dimensions are given in mm.

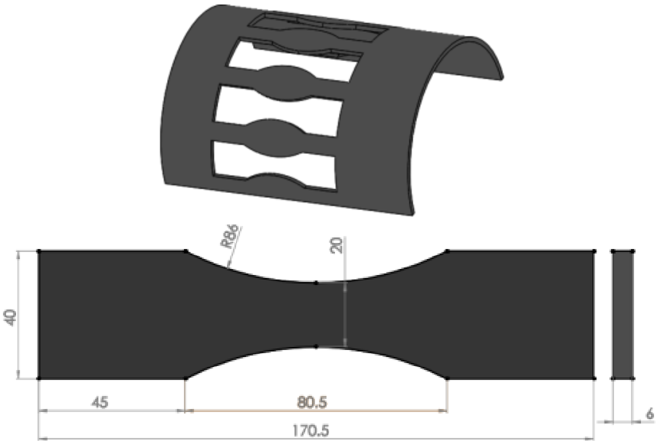

Figure 1. HDPE pipe section and specimen geometry.

Tensile tests are carried out at strain rates of 1.5×10^{-3} s^{-1}, 3×10^{-3} s^{-1} and 1.5×10^{-2} s^{-1}. Strain measurement is done by a contact extensometer. Particular attention is paid to the contact between the sample and the gauge to eliminate the sliding of the latter (Fig. 2).

Fatigue tests are carried out by the biaxial machine at Lille Mechanics Laboratory (LML). The platform is equipped with a servo-hydraulic cylinder with a maximum capacity of 100 kN, that can operate at high and low frequencies. The test is controlled by the Instron 8800 digital controller. The cylinder can be controlled by force, displacement, or strain. Figure 3 shows an overview of the test specimen assembly on the platform.

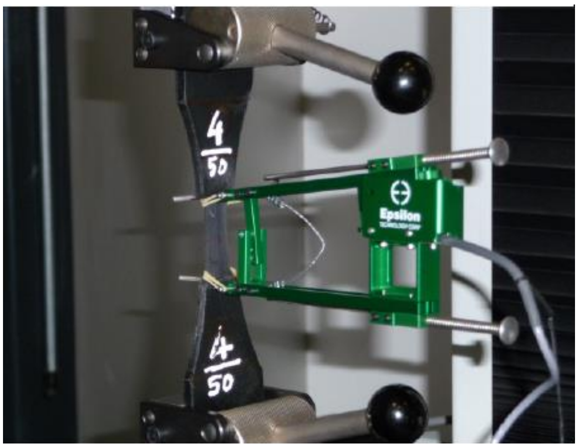

Figure 2. Measurement of strains on the sample during tensile test.

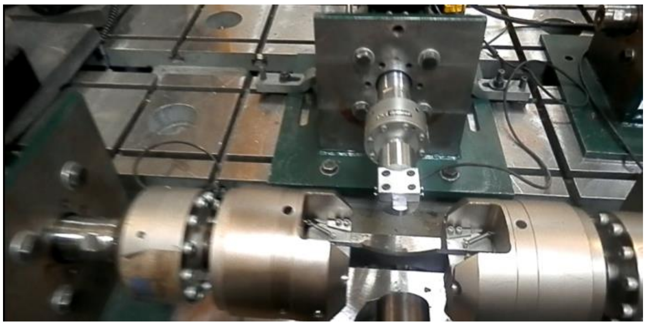

Figure 3. Overview of test specimen on the fatigue machine platform.

ANALYSIS OF RESULTS

Figure 4 shows the obtained results of tensile tests for different strain rates. These curves clearly show the significant effect of strain rate on the mechanical properties of HDPE, without affecting the overall behaviour of the material. This behaviour, marked by three domains, namely, elastic and viscoelastic, then a softening domain, where stress decreases as a function of strain, and then a perfect plastic plateau is observed before sample failure.

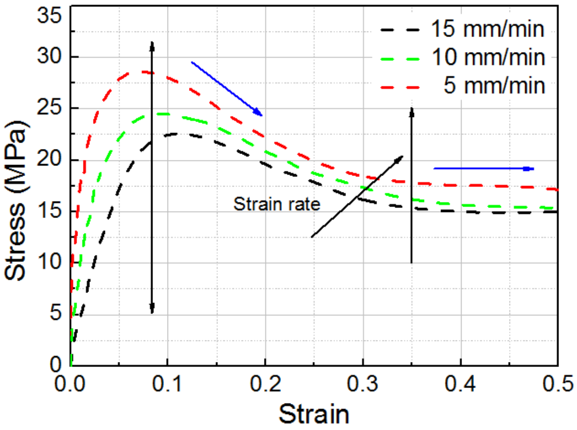

Figure 4. Results of tensile tests at different strain rates.

Fatigue tests are conducted at a load ratio R = 0.001 in order to avoid buckling of the specimen. The objective being to analyse the effects of frequency and stress amplitude, the tests are conducted with 3 stress levels, namely 19, 23 and 26 MPa. Each stress level has been tested under 3 frequencies, namely 1, 2 and 3 Hz. All tests are carried out at room temperature. Acquiring the data of stress as a function of strain during a cycle leads to the drawing of a loop shown in Fig. 5, called the hysteresis loop. The shape and size of these loops change depending on the number of cycles. It is observed that loops evolve over the life of the specimen with the dynamic modulus decreasing (inclination of the loop to the right). On the other hand, one can see the area included in these loops increases with the number of cycles. Thus, by calculating the area of the loop, we obtain the specific energy of viscous dissipation, as illustrated in Fig. 5.

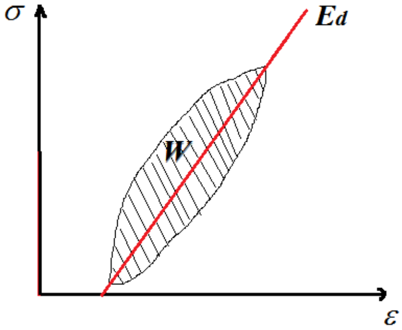

Figure 5. Scheme of a hysteresis loop and the method of calculating the dissipated viscous energy.

Figure 6 shows the loops obtained for a frequency of 1, 2 and 3 Hz under stress amplitude □=19 MPa and for the same cycle. In fact, an extension of the test piece is noted as the cycle number increases. This is traduced by kinematic of hysteresis loops during fatigue tests. In addition, for the same number of cycles, it is noted a high loop displacement under 3 Hz compared to 2 Hz frequency. This distance between the loops indicates a more increased softening effect at a high frequency and a frequency less than 2 Hz. Obviously, this effect is more pronounced for large numbers of cycles (100 cycle).

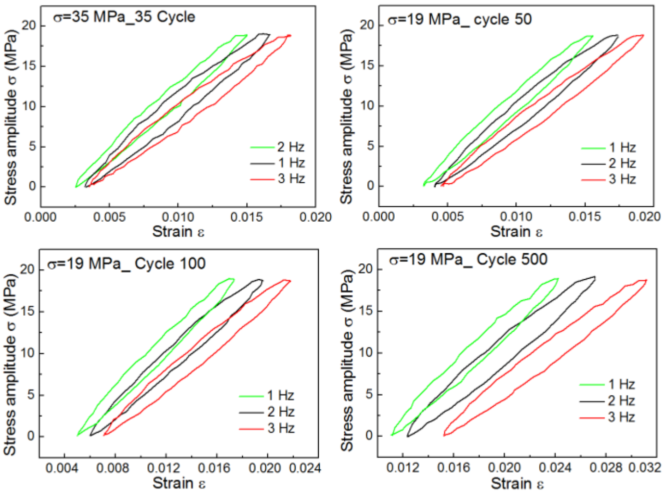

Figure 6. Hysteresis loops as a stress-strain record for different cycles under $\sigma = 19$ MPa, and different frequencies.

Another important fact is the widening of the loops as cycles increase. Effectively, according to Fig. 6, an extension of the test piece is noted as the cycle number increases. This is reflected by the higher strain level as the loops move toward the right. Another important fact is the widening of the loops as the cycles increase. As a result, the increase in the area included in the loop is more pronounced for the large number of cycles. Thus, the materials lose more and more energy which is transformed in localized heat. As a result, the life of the material decreases dramatically when the material is loaded at high frequencies and relatively less at low frequencies (Fig. 7).

Thus, by separating the loops and calculating the area of each loop, we obtain the results presented in Fig. 7.

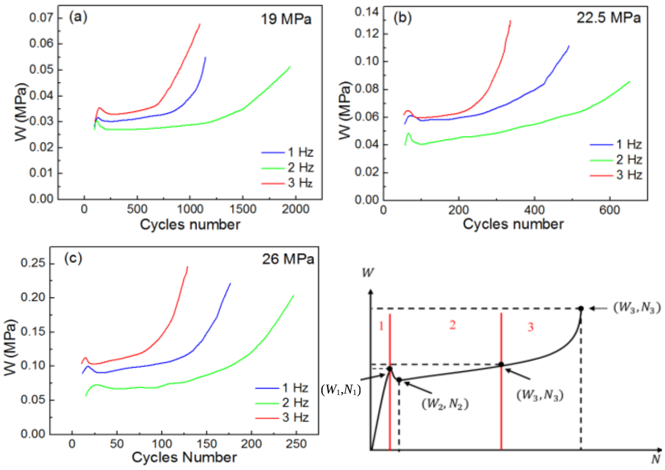

Figure 7. Dissipated energy v. cycle numbers, d) typical profile of dissipated energy vs. number of cycles and points delimiting the evolution domains.

Accordingly, Fig. 7 presents some results obtained during the experimental study which relate the energy dissipated to the number of cycles. These results confirm a significant effect of frequency on energy dissipation. In addition, this effect is not consistent since a frequency of 1 Hz causes more energy losses than frequency of 2 Hz.

Analysis of curves in Fig. 7 shows three types of energy evolution limited by three domains:

- in the first stage, there is a strong increase in energy, this stage represents the first few cycles of the fatigue life;
- in the second stage, representing the majority of the fatigue life, there is a slower increase in energy, with an approximately constant (linear) slope. The energy stabilizes during this stage regardless of test conditions;
- in the third stage, there is a rapid acceleration of dissipated energy until the specimen breaks.

In Fig. 7d, a typical example of the obtained profile is presented. Important points of the profile which delimit the three domains are identified and used as response data in the study and optimisation of the interaction effect of frequency and stress amplitude on the evolution of dissipated energy, and consequently, on the life of the material.

EXPERIMENTAL DESIGN APPROACH

Independent variables of this study for the analysis of fatigue behaviour of HDPE are stress amplitude and frequency of the test. As output data, we measure the area of hysteresis loops for load cycles. Thus, the viscous dissipation energy and corresponding number of cycles are output variables. In order to reduce the time and cost of the tests, the study intervals for different factors have been chosen so that the lifetimes are short (oligocyclic domain). Intervals for various factors are chosen according to the responses obtained from preliminary tests. Each parameter has been tested at three different levels: frequency f (1, 2 and 3 Hz) and stress amplitude σ (19, 22.5, and 26 MPa). Eleven experiments were necessary for the composite design in the range of variation of the two factors.

Table 1. Results of the design of experiments.

Exp	N	*f*	W1	W2	W2	W2	N1	N2	N3	N4
1	19	1	0.03199	0.0302	0.0326	0.05733	30	80	650	1100
2	26	1	0.09108	0.1062	0.2229	0.0910	8	20	97	172
3	19	3	0.03331	0.0359	0.0681	0.0333	31	90	600	1050
4	26	3	0.10436	0.1190	0.2485	0.1043	6	15	65	123
5	19	2	0.02664	0.0295	0.0516	0.0266	35	130	1100	1950
6	26	2	0.06714	0.0895	0.2050	0.0671	12	50	150	246
7	22.5	1	0.05821	0.0626	0.1110	0.0582	16	40	215	440
8	22.5	3	0.05986	0.0662	0.1301	0.0598	15	42	180	185
9	22.5	2	0.03966	0.054	0.0859	0.0396	20	50	350	600
10	22.5	2	0.03967	0.0540	0.0859	0.0396	22	52	352	602
11	22.5	2	0.03966	0.0540	0.0859	0.0396	21	51	350	601

For the experiment design, a complete two-factor plan with three levels is adopted. The suggested model is quadratic and has the following form:

$$y = a_0 + \sum_{i=1}^{2} a_i x_i + \sum_{1 \le j \le 2} a_{ij} x_j + \sum_{i=1}^{2} a_{ii} x_i^2 + e , \qquad (1)$$

where: a_0 is the predicted value of the response at the centre of the experimental domain; a_i is the effect of factor x_i; and a_{ij} is the interaction between factors x_i and x_j. The processing of responses using MODDE 5.0 /38/ software makes it possible to obtain response surfaces expressed in the form of polynomials. Thus, the proposed mathematical models and their coefficient lists are reported in Table 2.

Table 2. Coefficient lists in the models.

Outputs variables	Constant (a_0)	Coeff. (f)	Coeff. (s)	Coeff. ($f.s$)	Coeff. (f^2)	Coeff. (s^2)
W1	0.106607802	-0.03827982	-0.009397146	0.000373063	0.00812354	0.00035776
N1	151.4399559	12.07282257	-10.15574555	-0.088801714	-2.60085	0.172107755
W2	0.186804325	-0.040007051	-0.016113775	0.000328134	0.0087335	0.000486576
N2	785.9694035	58.66429284	-62.09589853	-0.162385429	-14.0442	1.210318367
W3	0.07704161	-0.038266393	-0.00696534	0.000397049	0.00802564	0.000313658
N3	6886.799639	528.8505071	-550.1901184	-1.666471429	-125.548	10.62930612
W4	0.424960133	-0.107648959	-0.039178818	0.000923946	0.023338	0.001234433
N4	12550.9448	959.3832286	-1011.492616	-2.740365714	-229.233	19.67559184

The coefficients of first and second-order terms and of the coupling terms provide information on the importance of their influence on the response, and their sign indicates the direction of variation. From the obtained mathematical models, one can determine the influence of each factor on the responses, by plotting the variation of the responses as a function of these chosen factors.

The evolution of dissipated energy (W1) and cycle number (N1) in the first stage as a function of the stress are presented, respectively in Figs. 8a and 8b. The analysis of Fig. 8a shows that an increase in the level of applied stress leads to a strong increase in dissipated energy (W1) and even a strong decrease in the number of cycles. Thus, it is noted that stress has a significant effect on dissipated energy and the number of cycles (N1) in the first stage.

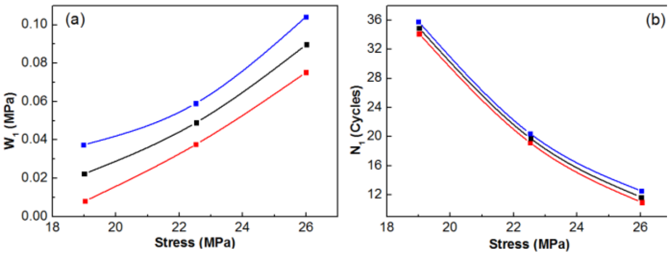

Figure 8. Effect of stress on the first stage: a) energy; and b) cycles.

The W1 and N1 responses predicted by MODDE 5.0 in the first stage are shown in Figs. 9a and 9b, which illustrate the influence of frequency on the results.

Analysis of Fig. 9a shows that increase in frequency is accompanied by a decrease in W1; this is valid for a frequency between 1 and 2 Hz. After that, the energy increases. Consequently, the number of cycles increases for frequency 2 Hz and decreases beyond this.

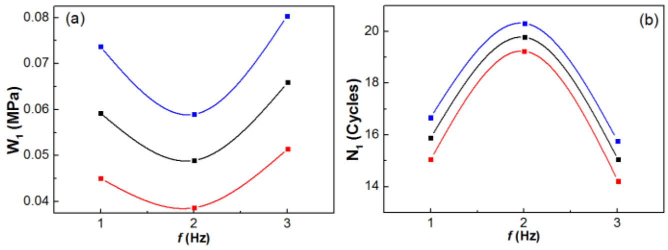

Figure 9. Effect of frequency on the first stage: a) energy; and b) cycles.

Figures 10a and 10b illustrate the effect of stress on the evolution of dissipated energy W3 and the number of cycles N3, respectively. By examining Fig. 10a, one notices that the stress always has a negative influence on dissipated energy. The increase of W3 is as stronger as the applied stress is higher, and thus accelerates the kinetics of damage. Figure 10b clearly shows that the number of cycles N3 is inversely proportional to the stress.

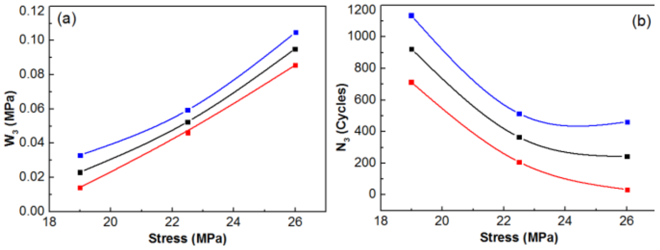

Figure 10. Effect of stress on the third stage: a) energy and b) cycles.

Analysis of Fig. 11a shows that the increase in frequency leads to a decrease in dissipated energy to reach a minimum value which corresponds to frequency of 2 Hz, beyond this frequency, energy increases. In the same way, it can also be observed an inverse trend in the evolution of the number of cycles N4 (Fig. 11b).

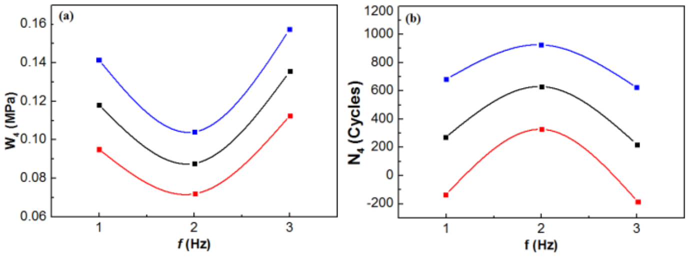

Figure 11. Effect of frequency on the fourth stage: a) energy; and b) cycles.

Consequently, the obtained results show that there is an optimum of frequency, and beyond it, the number of cycles decreases. Our results show that the number of cycles N3 is maximal for frequency of 2 Hz. On the other hand, at the highest or at the lowest frequencies, the life of the test piece decreases sharply, these results are in agreement with literature results /36, 37/. In other studies /39, 40/ carried out on the self-heating of reinforced polymers under cyclic stress, the authors observed a purely mechanical failure at 2 Hz.

Thus, it can be seen that the dissipated energy and consequently the lifetime depends both on the amplitude and on the frequency of the applied stress. Primarily, there should be test frequencies suitable for different stress levels.

To better understand the fatigue behaviour of the HDPE in the study and to set the appropriate frequency and stress levels, a quantification of interactions between frequency and stress is necessary. These interactions are carried out by visualizing the variation in dissipated energy and number of cycles by a three-dimensional graph in Figs. 12a and 12b. The latter show variations of W1 and N1, respectively, as a function of these two factors.

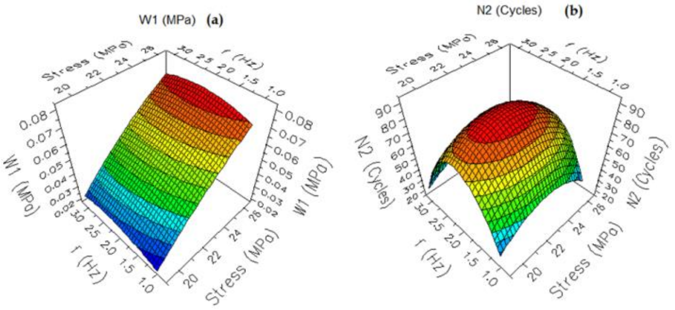

Figure 12. 3D variation: a) energy; and b) cycle number.

Figure 12a shows the predicted response (W1) as a function of the two factors. In this first stage, it is noticed that low energies are obtained for frequencies between 1.25 and 2.75 Hz. Energy is more dissipated at higher or lower frequencies. On the other hand, it can be observed that the dissipated energy increases and decreases respectively with the increase and decrease of applied stress, whatever the value of frequency. This leads to low numbers of cycles for higher or lower frequencies. The greatest number of cycles in the 1st stage is noted for stresses between 19 and 20 MPa for the same frequency range (Fig. 12b).

For the second and third stages where larger numbers of cycles are obtained, the same frequency range, namely 1.25 and 2.75 Hz causes the lowest energy losses (Fig. 12c and 12e). It is revealed a slight difference concerning the extent of the corresponding stress level for the third stage. Indeed, Fig. 12e shows that stress of 21 MPa would cause less energy with a frequency between 1.75 and 2.25 Hz than would do the stress of 19 MPa with a frequency lower than 1.25 Hz or higher than 2.75 Hz. This implies a combined effect between stress and frequency and therefore, a frequency suitable for low-stress levels is not suitable for high-stress levels and vice-versa (Fig. 12f).

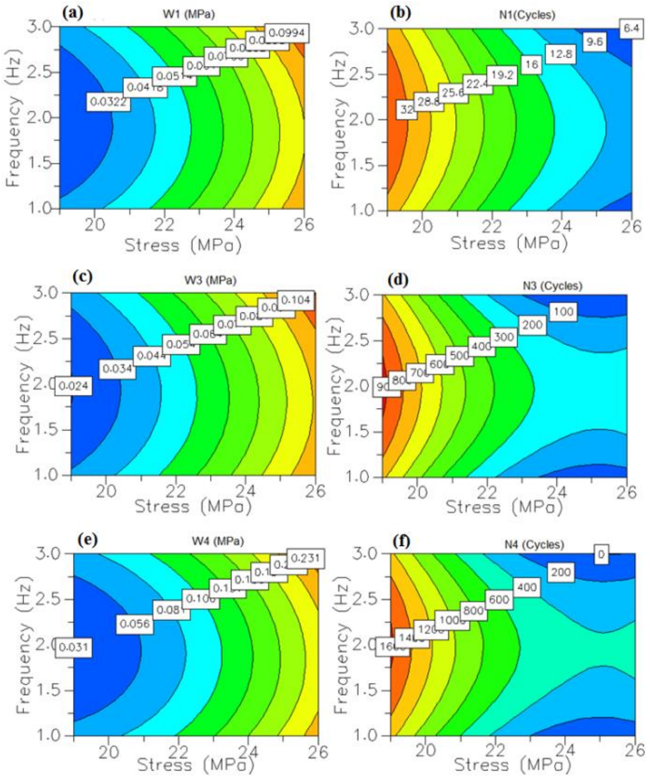

Figure 12. Iso-surfaces of energy and cycles variations as a function of the two factors.

Being this, it is important to analyse effects of different factors on the evolution of dissipated energy and the number of cycles. This would allow us to decide which parameter has the greatest influence and how the parameters interact.

This is done by means of histograms in Figs. 13a to 13d which show the effect of different factors for the third stage. These figures highlight the effects of factors using a bar chart with the effects in descending order according to their importance in absolute value.

Analysis of Fig. 13 shows that dominant factors are in order: stress and frequency. The effect of stress is more significant compared to frequency. On the other hand, the quadratic effect of the frequency is more important compared to the quadratic effect of stress. In addition, it should be noted that the effects of frequency and stress are opposite. In other words, if the effect is positive on energy (Figs. 13b and 13d), it is even negative on the number of cycles (Figs. 13a and 13c).

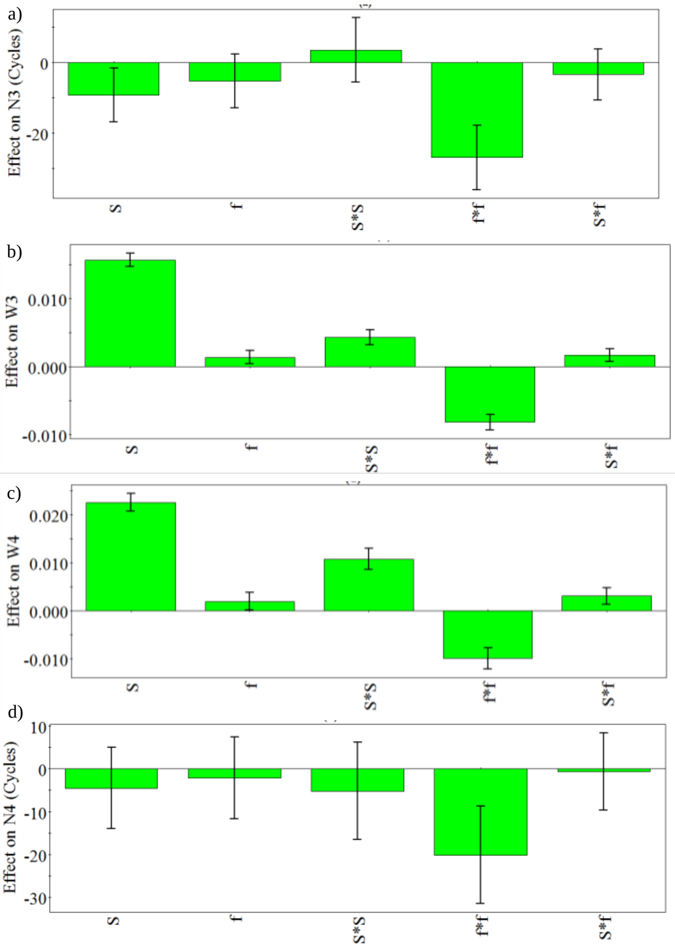

Figure 13. Effects of factors on energy and cycle number and their interaction.

CONCLUSION

The objective is to analyse experimentally the interaction effects of stress and frequency of the test on the extent of dissipated energies during lifetime of HDPE material. Static tensile and fatigue tests are carried out to characterize static and cyclic material behaviour. Static tests have shown the viscoelastic nature of the HDPE material whose behaviour depends on strain rate. Fatigue tests are done under different frequencies (1, 2 and 3 Hz) and different stress amplitudes (19, 22.5 and 26 MPa). This was to analyse the effect of the latter parameters on cyclic behaviour of the material. The obtained results led to the following conclusions:

- the cyclic behaviour of HDPE is characterized by kinematic hysteresis loops whose slope and area change with number of cycles. This is more pronounced for large numbers of cycles, where the increase in area included in the loops is observed;
- dissipated energy traduced by the surface integration of stress-strain loop during a cycle depends strongly on the stress amplitude and the test frequency;
- regardless of frequency and stress amplitude, dissipated energy vs. cycle number presents a trend characterized by:
  1. High energy dissipated through the few first loading cycles, this represents the first stage.
  2. In the second stage, the energy decreases and then slowly increases in a linear trend.

3. When reaching a certain number of threshold cycles, the energy increases sharply until the sample breaks. This represents the third stage of behaviour.

- the experimental design method made it possible to achieve a better knowledge of the phenomena observed through a minimum of tests;
- the increase in frequency has a paradoxical effect. Indeed, a low frequency causes more consequent energy losses than a frequency in the vicinity of 2 Hz. However, higher frequency also causes more consequent loss of energy;
- the effect of stress amplitude is more significant compared to frequency;
- it is important to optimise the choice of frequency to minimize energy and extend service life.

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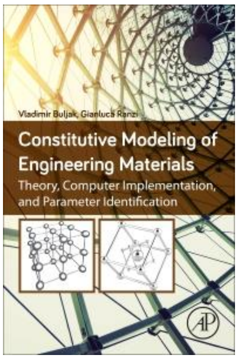

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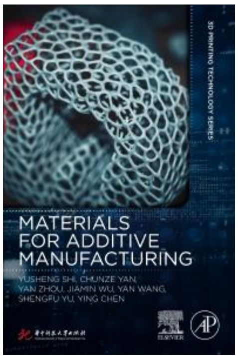

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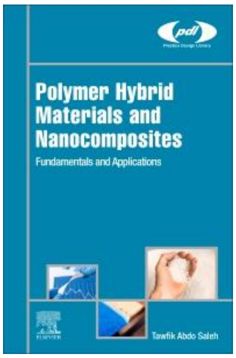

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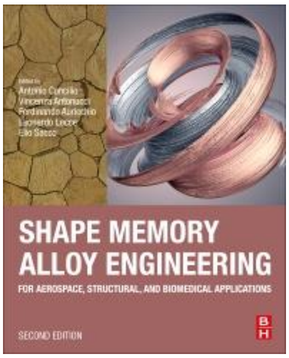

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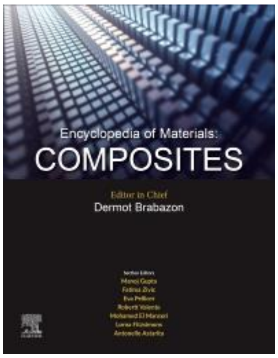

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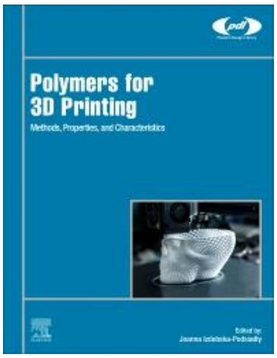

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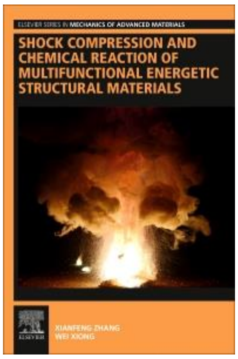

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