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Modelling the Temperature Aging Effect on Tensile Fracture Load of Notched High Density Polyethylene Material Using the Planning Design Experiment Approach

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Abstract

This article addresses the experimental characterization of the temperature aging effect on tensile fracture load behavior of notched and unnotched high density polyethylene material. The samples were cut from a HDPE pipe. After mechanizing the tensile specimens with a numerical controlled machine, two series of samples were mechanized with different types of notches. The first series was drilled with a different central hole of diameter 4,6 and 8 mm. In the second series, one group of specimens the V shape notches were carried out on one side of samples, while for the second group the V shape notches were carried out on the double sided of specimens. Once the notches mechanized, the samples were exposed into a room temperature to positive and a negative temperatures -40°C and 100°C during 72 hours. The planning design experiment approach was applied to obtain a mathematical model taking account all the influencing parameters on tensile fracture load of the material. The fracture tensile load and the elongation in cases of V and circular notch were modeled as function of temperature aging effect. From the response surfaces of both cases, we note that the temperature had a significant effect on fracture load tensile and elongation with respect on type of number of V notch and hole diameter. The ultimate tensile load decrease and the elongation increases.

Keywords: High density polyethylene; Tensile fracture load; Central circular notches; V notches; Temperature aging; Planning design experiment approach

Introduction

The pipes are used in the most diverse application areas including water, waste water and sewer pipes. Recently, the material based on polyethylene becomes more and more dominant in pipe industry. The polyethylene pipes are exposed to different varieties of aggressive environments such as marine, chemical environments, humidity, wide range of temperature, ultra violet exposure. This environment can affect their lifetime involving the deterioration of their physical and mechanical properties. High Density Polyethylene (HDPE) is a material widely used for the distribution of drinking water and natural gas. Macroscopic cracks can initiate and propagate in industrial components during service under the influence of time-dependent creep strain. The knowledge developed on Fracture Mechanics of Creeping Solids is nowadays used for applications such as thermoplastic pressure pipes for water, sewer services and natural gas supply. The absorbed humidity can decrease the mechanical properties of the polymer, like the ultimate strength. Also the moisture diffusion affect the glass transition temperature (T_g) of the polymer. The strength of polymers is known to be sensitive to temperature and this generally limits their use under service temperatures lower than the glass transition temperature. High Density Polyethylene (HDPE) is an attractive material for scientific and technological studies due to its low cost, good properties and versatility. Many studies have been conducted over the years to investigate various aspects [1-8]. Environmental parameters acting on a polymer such as temperature, humidity, chemical exposure, radiation, biological agents, and their combinations were investigated. Many investigations were conducted, L. Laiarinandrasana et al. [1], have characterized the mechanical behavior of HDPE pipes, using the ASTM D 2290-04. The specimens were tested to tensile strength. Also the ageing effect of the pipe was investigated by determining the strain at failure. A numerical study based on the finite element method using a constitutive model was conducted by Kwon et al. [2].

The finite element method was applied in order to simulate deformation behavior of high-density polyethylene (HDPE) when subjected to tensile loading, without or with the presence of pre-cracks Hamouda. [3] have investigated the effect of temperature on creep behavior of a medium density ethylene–butene copolymer (MDPE) using both asymmetrical Full Notched Tensile (FNCT) and Double Edge Notched Tensile (DENT). The samples were tested at temperature about 60°C. The incremental damage approach was made to study the long term failure of a component under creep conditions. The observations of the experimental creep were also compared to the creep stress–strain calculated by the numerical finite element method. Cerqueira et al., have studied the mechanical properties of polypropylene reinforced with fibers composites [4].

The main of the investigation was to determinate the effect of chemical modification on mechanical properties of a composite of sugarcane bagasse fiber. In order to allow a high tensile modulus the fibers were pretreated with 10% sulfuric acid solution, and the followed by delignification with 1% sodium hydroxide solution. The matrix was a polypropylene, the volume fibers varies on 5 to 20 wt%. Results

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presentamelioration of tensile load, flexural and impact strength of the composite materials in comparison with the polymer pure. Alpay Oral et al., used the Gurson Tvergaard Needleman model, commonly used for metallic materials [5]. The model was applied to the failure of a polymeric material. Gurson Tvergaard Needleman had modeled the parameters for this material using the simplex method correlating with experimental and numerical results.

Necmi Dusunceli and Bulent Aydemir, conducted a series of experiments to determine the effects of loading effect on mechanical behavior of high- density polyethylene (HDPE) [6]. The main reason for undertaking the research was to investigate multiple creeps, multiple relaxation, and cyclic loading on uniaxial tension. The samples used for tensile tests were obtained from pipe. Understanding the deformation behavior under different loading can offer the designer of high-density polyethylene products reliable data relevant to practical applications.

Bagherzadeh et al., conducted the analysis of the stretch-blow moulding (SBM) process of polyethylene terephthalate (PET) using the finite element method (FEM) [7]. The parts are considered as an axisymmetric model. Through the study, it becomes clear that the proposed model is applicable for simulating the stretch-blow moulding process. Merah et al., investigate the effect of temperature on tensile properties of HDPE pipe under a range of temperature from -10°C to 70°C according to ASTM standard [8]. Yield stress and modulus of elasticity are found to decrease linearly with temperature. The average yield strength decreased linearly from 32 to 9 MPa when the temperature is increased from -10 to 70°C. Szpieg et al., studied a fully recycled carbon fiber reinforced maleic anhydride grafted polypropylene (MAPP)-modified polypropylene (rCF/rPP) composite material [9]. The results revealed a significant reduction in fiber length by the press-forming operation. To model the viscoelastic and viscoplastic responses of the composite an inelastic material model was employed using a series of creep. From the creep tests, it was found that the time and stress dependence of viscoplastic strains follows a power law.

Experimental Procedures

Materials

The tensile behaviour of high density polyethylene material (HDPE) was investigated. The Table 1 present the mechanical properties of the HDPE [1]. Raw materials of HDPE in the form of dried plastic pellets were subjected to high-pressure injection molding machine to obtain the pipe for mechanical tests as per ASTM standard.

Preparation and conditioning of specimens

The standard tensile specimen is derived from the pipes HDPE, which is characterized by a diameter of 100 mm (Figure 1a). These sample coupons were cut in the longitudinal tube. First the sample coupons were cut from a HDPE pipe, and then mechanized using the numerically computer controlled machine. The specimen dimensions were: Length 120 mm, width 20 mm and thickness 3.5 mm. Two series of samples were mechanized with different types of notches. The first series was drilled with a different central hole of diameter 4, 6 and 8 mm.

Mechanical properties	
Density	0.948 g/cm^3
Hardness, Shore D	62
Tensile strength	30 MPa
Elongation	840%
Tensile modulus	0.86 GPa
Flexural modulus	0.928 GPa
Izod Impact, Notched	3.7 J/cm
Coefficient of friction	0.28

Table 1: Mechanical properties of HDPE.

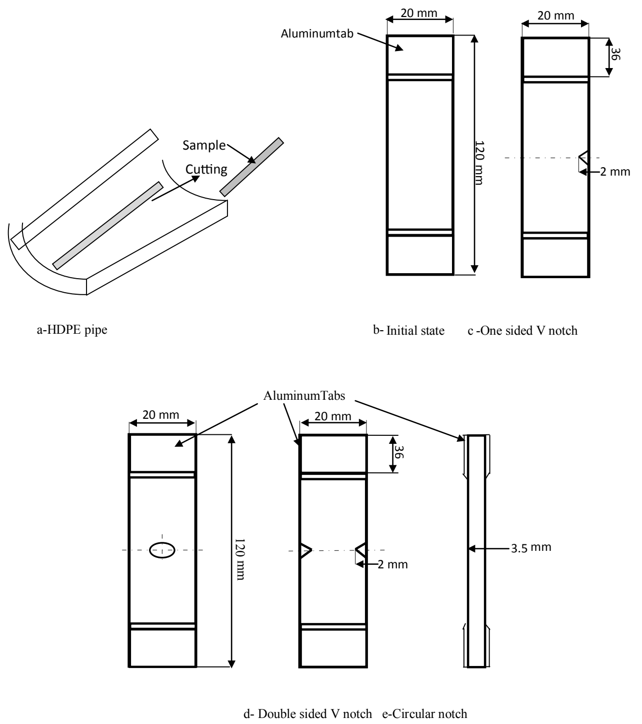

Figure 1: Unnotched and notched tensile specimen.

In the second series, the V shape notches were carried out on one side of samples, while for the third series the V shape notches were realized on the double sided of specimens, (Figure 1b, c, d and e). The V notch had the dimension of 2 mm dept and an angle of inclination of 45°. The specimens were subjected into a room temperature to -40°C and 100°C during 72 hours. In order to avoid the stress concentration at the attach points; the Aluminum tabs were glued to both sides of all the specimens using an adhesive 3M.

Tensile fracture test

After temperature conditioning, the specimens were tested to tensile fracture, three specimens of each series were tested according to ASTM D3039 using an Instron machine at a constant loading rate of 0.5 mm/min [10]. The average tensile fracture and elongation values were recorded for each specimen (Figure 1).

Description of Planning Design Approach

The design of experiment method is used in general to obtain a mathematical model taking account all the influencing model parameters. Design of experiments is thus a discipline that has very broad application across all the natural and social sciences and engineering. A methodology for designing experiments was proposed by Fisher [11].

Results and Discussion

Case of V notch

Tensile load modeling: First the tensile fracture load was modelled

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Number of Exp.	Coded V notch	Coded T Temperature	Coded VT V notch -temperature	T*	Y_1 (N) Tensile load	Y_2 (N) Tensile load	Y_3 (N) Tensile load	$Y_{average}$ (N) Tensile load
1	-	-	+	1/3	3800	2301	2943	3014,66
2	+	0	0	- 2/3	3450	3900	3020	3423,33
3	-	+	-	1/3	3950	2543	2900	2997,66
4	+	-	-	1/3	3900	2200	3150	2983,33
5	-	0	0	- 2/3	3837,02	3002,76	4606,56	3815,44
6	+	+	+	1/3	2800	2100	3493	2797,66

Table 2: Values of tensile load variation as function of the coded V notch and coded temperature.

Number of Exp.	Coded V notch	Coded T Temperature	VT Coded V notch-temperature	T*	Y_1 (mm) Elongation	Y_2 (mm) Elongation	Y_3 (mm) Elongation	Y_{averae} (mm) Elongation
1	-	-	+	1/3	14,01	9,63	18,77	14,14
2	+	0	0	- 2/3	17,17	15,66	16,35	16,39
3	-	+	-	1/3	20,25	17,64	21,58	19,82
4	+	-	-	1/3	13,37	13,01	13,92	13,43
5	-	0	0	- 2/3	19,44	16,61	18,47	18,17
6	+	+	+	1/3	16,94	16,8	19,95	17,89

Table 3: Elongation variation as function of the coded V notch and coded temperature.

by applying the planning design experiment approach [12-15]. The Table 2, shown the coded values and the average fracture loads.

The mathematical model taking account the number of the V notch and the temperature was listed in equation (1):

$$Y(xi,\beta) = 7252,10 - 2438,55X_1 - 42,33X_2 - 2500,25X_{12} - 1072,32X_{11}^2 \quad (1)$$

Where:

X1: Represent the notch type (single V and double V),

X2: Represent the temperature,

Y : Represent the tensile fracture load (N).

Figure 2 present the curve variations of tensile fracture load as function of temperature and the number of V notch. We note that the tensile fracture load increase linearly from a single notch to a double notches for a decrease in temperature from 100°C to 68°C, and no linearly and rapidly reaching the temperature of 8.8°C, followed by a no linearly and slowly reaching the value of -40°C. The tensile fracture load decrease no linearly for double V notches with a diminution in temperature. The optimal value of the tensile fracture load was 7288.5 N. The tensile test results of plain specimen show a significant difference between the engineering and true properties especially for ultimate load.

These differences can be attributed to the large elongation of HDPE specimens during the tensile test and the corresponding reduction in their cross sectional area. The tensile test results of notched HDPE specimens indicated that the presence of notches altered the axial engineering behaviour of the tested material.

Elongation modeling: The elongation was modeled by the planning design experiment approach. In Table 3, we present the variation of elongation as function of V notch number, the temperature and average elongations.

Applying the planning design experiment approach, the mathematical model taking account the number of V notch and temperature was listed in equation (2).

$$Y(xi,\beta) = 34,17 - 11,40X_1 + 2,53X_2 - 14,64X_{12} - 2,77X_{11}^2 \quad (2)$$

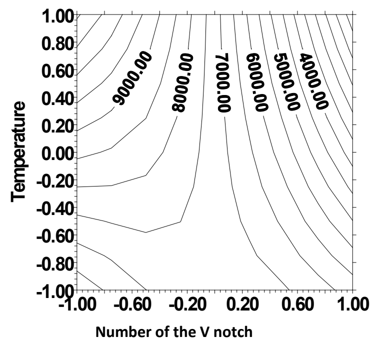

Figure 2: Effect of the number of the V notch and the temperature on the tensile fracture load.

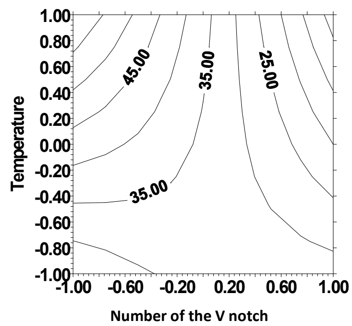

Figure 3: Effect of the number of V notch and the temperature on the extension.

From Figure 3, we note that the elongation decrease no linearly and slowly in the case of double notches as function of a decrease in temperature. In the case of a single V notch, the elongation increase slowly as function of temperature. The elongation presents a minimum-maximum about 29.76 mm.

Case of circular notch

Tensile load modeling: The tensile fracture load was modelled by

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Number of Exp.	Coded D diameter	Coded T temperature	Coded DT	D*	T*	Y_1 (N) Tensile load	Y_2 (N) Tensile load	Y_m (N) Tensile load
1	-	-	+	1/3	1/3	2591	2764,32	2677,66
2	0	-	0	- 2/3	1/3	2219	2397	2308
3	+	-	-	1/3	1/3	2075	1770.32	1922,66
4	-	0	0	1/3	- 2/3	4062	4088	4075
5	0	0	0	- 2/3	- 2/3	2839	2813.66	2826,33
6	+	0	0	1/3	- 2/3	1595	1678.34	1636,67
7	-	+	-	1/3	1/3	2826	3362	3094
8	0	+	0	- 2/3	1/3	2877	2639	2758
9	+	+	+	1/3	1/3	2108	1704	1906

Table 4: Tensile fracture load variation as function of the coded notch diameter and coded temperature.

Number of Exp.	Coded D Diameter	Coded T Temperature	Coded DT	D*	T*	Y_1 (mm) Elongation	Y_2 (mm) Elongation	Y_m (mm) Elongation
1	-	-	+			12,45	13,03	12,74
2	0	-	0			15,87	5,99	10,93
3	+	-	-			6,91	4,75	5,83
4	-	0	0			14,14	9,58	11,86
5	0	0	0			4,92	4,02	4,47
6	+	0	0			5,34	3,80	4,57
7	-	+	-			13,63	12,87	13,25
8	0	+	0			10,88	9,19	10,03
9	+	+	+			7,02	5,26	6,14

Table 5: Elongation variation as function of the coded notch diameter and coded temperature.

applying the planning design experiment approach [12-15]. In Table 4, the coded values and the average loads were presented.

From Figure 4, We note that the variation in temperature from -40°C to 100°C, the tensile load decrease no linearly by increasing the notch diameter from 4 to 8 mm. The mathematical model taking account the hole diameter and temperature was listed in equation (3).

$$Y(xi,\beta)=2898{,}518-730{,}22X_1+141{,}61X_2-108{,}25X_{12}-78{,}78X_{11}^2-401{,}61X_{22}^2 \quad (3)$$

Elongation modeling: The mathematical model describing the elongation variations as function of temperature and notch diameter was given in equation (4) Table 5.

$$Y(xi,\beta) = 1.026-2.13X_1-0.2X_{12}+1.17X_{11}^2+5.71X_{22}^2 \quad (4)$$

By varying the notch diameter from 4 to 8 mm, the elongation decrease linearly and rapidly for a variation in temperature from -40°C to 24.4°C followed by a no linearly and rapidly decrease in temperature of 24.4°C to -0.4°C and linearly and slowly from -0.4°C to 20°C. The elongation increase slowly from 20°C to 50.6°C followed by a no linear variation from 50.6°C to 65.6°C. Equally, it is clearly shown that the aging temperature influences the level of the mechanical degradation: higher is the aging temperature, more important is the mechanical degradation (Figure 5).

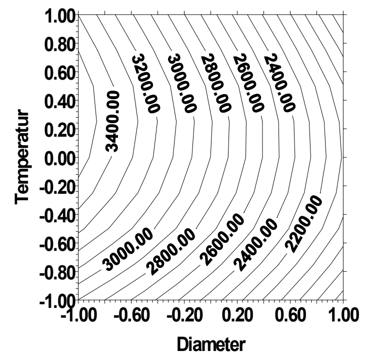

Figure 4: Effect of notch diameter and temperature on the tensile fracture load.

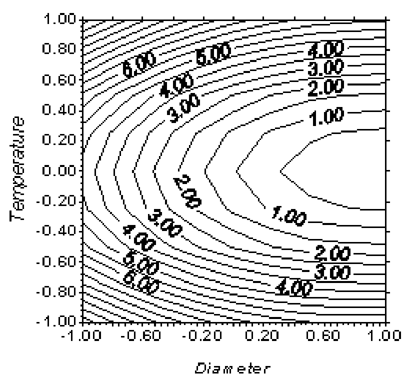

Figure 5: Effect of notch diameter and temperature on the elongation.

Conclusion

The main goal of the paper was to investigate the temperature aging effect on the notched and unnotched tensile fracture load of a High Density Polyethylene material. The specimens were cut from a HDPE pipe and then mechanized using a controlled machine. The specimens were mechanized with two different types of notches. Two series of samples were manufactured with different types of notches. The first series was drilled with a different central hole of diameter 4, 6 and 8mm. In the second series, the V shape notches were carried out on one side of samples, while for the third series the V shape notches were realized on the double sided of specimens. The samples were subjected to aging into a room temperature to -40°C and 100°C during 72 hours and then tested to tensile load using an Instron machine. In order to obtain mathematical models describing the effect of temperature, a type and a number and sizes of notches, the planning design experiment approach was used. In each case, the tensile fracture load and the elongation were modeled by the planning design experiment approach. The tensile load decrease as function of diameter increase and temperature. Decreases of such mechanical properties as function of aging temperature were also observed. The structural modifications and chemical changes occurring in the HDPE polymeric chains. Mechanisms intervening in degradation are the following:

1- Chain breaking caused by homolytic and heterolytic dissociation.

2- Branching and cross-linking formed by radicalary addition.

Aging of polymeric material under normal service conditions is a difficult case to treat. Most of the studies are based on accelerated aging test and required extrapolation to normal service conditions.

• Many factors can significantly affect the durability of a polymeric material, such as temperature, irradiation, moisture, chemicals.

• Synergism in the global aging often occurs when the simultaneous action of several stresses results in an aging effect that differs from that which would be observed if the individual stresses were applied sequentially.

• Aging models have a limited used for practical applications because real life aging conditions are usually far more complex than what can be simulated in laboratory. When assessing the conditions of a polymeric material is critical.

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