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Experimental Study on Fracture Toughness of HDPE Material with Compact Tension Specimens for Small Vessel

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ABSTRACT

Non-ferro materials in use for ship structures require characteristics that meet the requirements. This research conducted a study and testing of High-Density Polyethylene (HDPE) material in the form of plates with type PE 100. The investigation was carried out with mechanical testing to obtain mechanical properties of HDPE. The purpose of this research is to obtain mechanical properties including tensile strength, ultimate strength, elongation, and Fracture Toughness of this material. In this case, the Fracture Toughness value is obtained using a compact tension specimen. The variation given in this research is to provide artificial defects on the side of the material and without any side grooves. Based on the test results, it is known that the yield strength, ultimate strength, and elongation of the material meet the acceptance criteria, and the fracture Toughness value obtained in this test in both variations is 1.64 Mpa. Where this value does not meet the criteria of the fracture Toughness value.

Keywords:

Non-ferro material; Ship structures; High-density polyethylene; Fracture toughness

1. Introduction

One type of plastic whose use continues to increase is High-Density Polyethylene (HDPE). This type of plastic itself is in high demand worldwide, with a market volume of around 30 million tonnes per year [16]. The use of polymer materials is increasing in various structural components. For example, it is used in ship hull structures or as pipes often found today [9,19]. HDPE itself is a linear thermoplastic polymer made from ethylene monomer [2]. HDPE is a type of plastic material with higher strength than other types of plastic because it has more rigid properties and is resistant to impact [12,17,22]. In addition, HDPE is a more environmentally friendly material because it can be recycled [11].

The advantages of HDPE material are substantial, complex, resistant to high temperatures, and light density. The density of HDPE material ranges from 930-970 kg/m^3 [21]. The fracture mechanics method is a method that is primarily used to measure the fracture toughness of a material structure [5]. Because of the extensive usage requirements, this method is appropriate for a viscoelastic

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material. One of the methods used to analyse the application of pre-crack can be done for the approach. Some studies show that stimulation of the ideal crack and into the crack tip can be made using a razor blade and can cause damage to the polymer matrix, so it must be observed to obtain fracture toughness results [13,14].

HDPE material is highly advantageous and ideal for use in the shipping industry [20]. It has been extensively used in the production of small boats like patrol boats, speedboats, rescue boats, and lifeboat [19]. This material has numerous benefits, including resistance to high-impact loads, excellent tensile strength, the ability to withstand continuous temperature changes, and resistance to scratches, dirt, and corrosion [15]. These properties make it an excellent choice for ship operations.

The study of standards for the use of polyethene materials in the shipping industry is explained in the Tentative Rules for Polyethylene Craft [21]. Besides that, before it was done on metal, the crack was easy to open with controlled cycle, load, and standard conditions [8]. However, it is challenging to determine relaxation for fatigue for viscoelastic materials such as polymers, which have cycles. Toughness is the ability or capacity of a material to absorb energy until it fractures, or toughness is the resistance of a material against breaking in two with a transverse crack [1]. Tests for toughness against cracking of HDPE materials which are plastic-based are specified in the Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials [4] and Plastic-Determination of Fracture Toughness (KIC) and Linear Elastic Fracture Mechanics (LEFM) Approach [10].

Therefore, this study aims to evaluate the strength and toughness of HDPE material on ships with acceptance criteria under applicable standards.

2. Methodology

2.1 Research Purposes

The material's toughness can be determined by conducting fracture testing with compact tension specimens. This study aims to:

i. Knowing the mechanical properties of HDPE material
ii. Obtain the toughness value of HDPE material due to cracks.

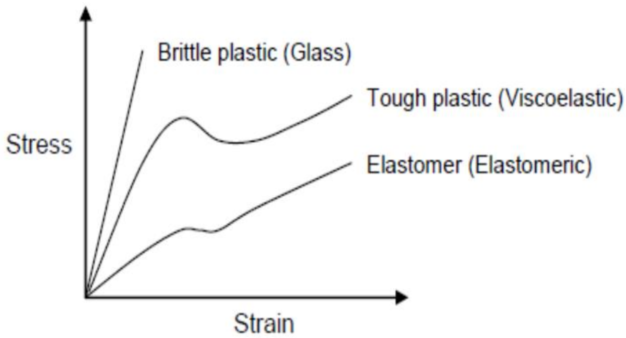
2.2 Tensile Strength

The tensile test is one of several tests commonly used to determine the mechanical properties of a specimen. Tensile testing is a method used to test the strength of a material by providing an axial force load. In the tensile test, a standard specimen is used which is gripped in a testing machine, then the object is pulled at a certain loading speed until the specimen is divided into two or broken. Then, all the data obtained from the test will be arranged in one diagram called the standard stress-strain diagram using acceptance criteria as shown in Table 1.

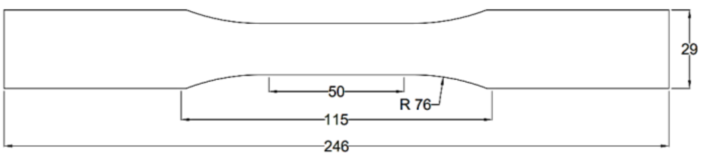
Table 1
Acceptance criteria standard for HDPE material [21]

Property	Requirement HDPE	Unit	Test Method
Tensile Yield Stress	Min. 17	N/mm2	ASTM D-638
Tensile Break Stress	Min. 14	N/mm2	ASTM D-638
Ultimate Tensile Stress	Min. 24	N/mm2	ASTM D-638
Tensile Elongation at Yield	1 to 27	%	ASTM D-638
Tensile Elongation at Break	10 to 1500	%	ASTM D-638

In polymers, there are three types of stress-strain curves. Most crystalline polymers can exhibit viscoelastic properties [16]. The stress-strain curve begins with a straight line as strain increases, and the stress at which slip becomes visible and significant. In this material you can see the characteristic differences in the polymer material in Figure 1.



(a)



(b)

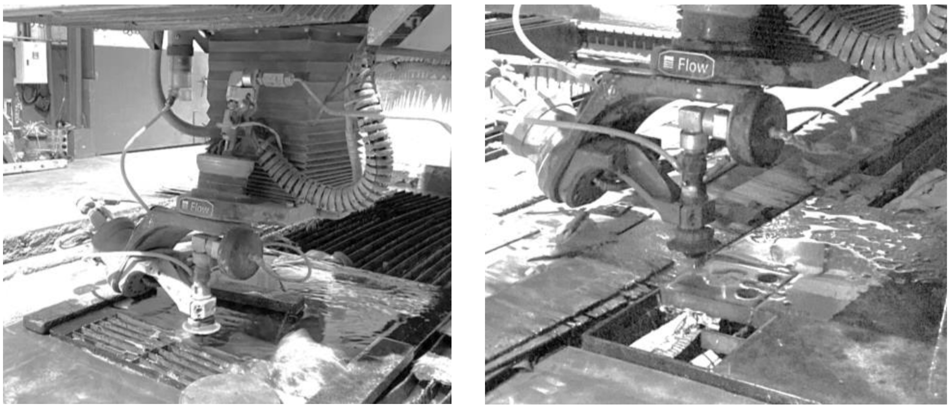
Fig. 1. Polymer Materials; (a) stress-strain diagram, (b) detailed specimen dimensions [3]

To determine the tensile strength of the material is carried out based on the ASTM D-638 standard [3]. The material design used is type III, following the rules used for plastic testing. Specimen data collection was carried out to obtain data on width (W), thickness (t), and initial area (Ao) and to provide Gauge Length (Lo). This data is presented in Table 2.

Table 2
Tensile test specimen data

No.	Width (mm)	Thick (mm)	Length (mm)	Length (mm)	
	W_o	T_o	A_o	L_o	L_1
T1	19.46	9.82	191.10	50	136.43
T2	19.48	9.85	191.87	50	188.39
T3	19.44	9.83	191.10	50	267.28
T4	19.41	9.82	190.60	50	181.04
T5	19.43	9.81	190.60	50	194.88
T6	19.44	9.85	191.48	50	206.40
T7	19.41	9.84	190.99	50	138.54

The specimen shape process was carried out with the help of a waterjet laser cutting, considering that there was no heat treatment, and no characteristics were changed. The process of cutting the specimen is shown in Figure 2.



(a) (b)

Fig. 2. Cutting specimen processing; (a) Tensile, (b) compact tension

2.3 Fracture Toughness Test

This test is a destructive test which aims to determine the value of material toughness (Kic). The test specimens used in this test comply with ISO 13586 standards. The thickness of this material is 20 mm, and the width varies by 125 m, 100 mm and 40 mm. HDPE material is tested by crack. The notch is made with a razor blade. The process of making cracks can be done by two methods, as follows:

i. Make a sharp notch into the test piece and then make a natural crack by tapping a new razor blade placed in the notch (this is important to do because, in brittle test pieces, natural cracks can be produced by this process, but some skill is required to avoid cracks or prolonged local damage). The length of the crack created must be more than four times the radius of the original notch tip.
ii. Natural cracks cannot be produced, as in a challenging test piece, so sharpen the notches by sliding a razor blade across the notches. Use a new razor for each test object. The length of the crack created must be more than four times the radius of the original notch tip.

This fracture toughness test uses a tolerance factor of 0.50 and in this study the precrack is 50 mm. planned according to the standard parameters shown in Figure 3.

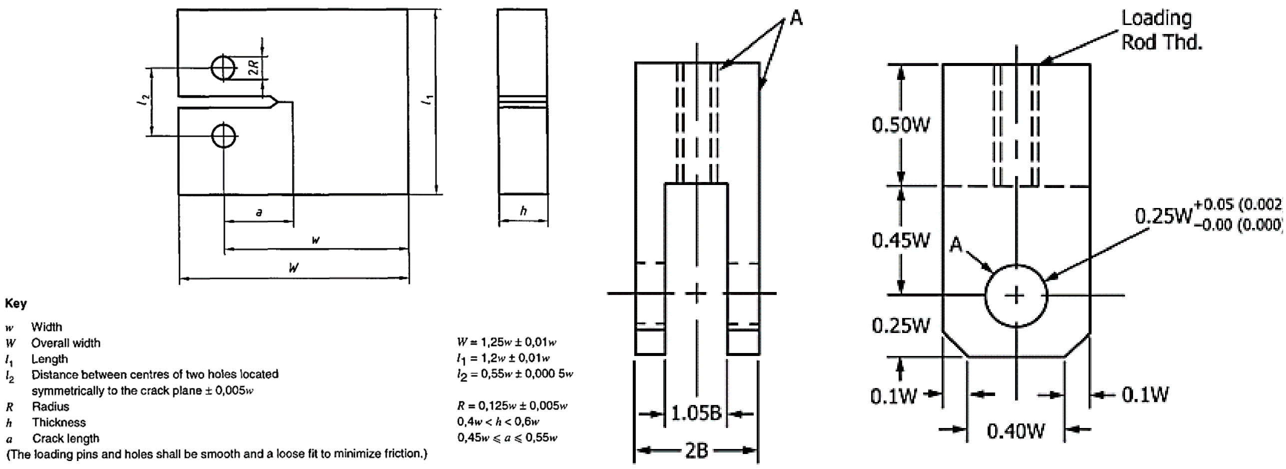


Fig. 3. (a) Toughness Test Specimen and (b) Compact Tension Specimen Grip Design (ISO-13586 2018)

Figure 4 shows variations of compact tension specimens. The test procedure uses a device designed according to the standard. The test process is carried out by calculating a value with an accuracy of 0.5%. Measure width (W) to 0.1%. In testing viscoelastic materials, it is necessary to determine the temperature and time scale in which the results are obtained. As primary test conditions, it is recommended to use a temperature of 23°C and a crosshead rate of 1.67 × 10−4 m/s (10 mm/min).

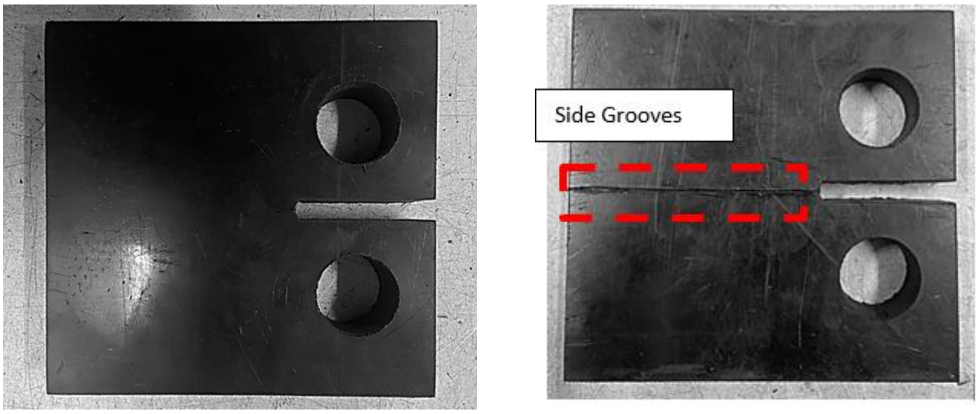


Fig. 4. Variation of compact tension specimen models: (a) no crack, and (b) side grooves

Calculating the KQ value to determine KIC follows the approach method with Linear Elastic Fracture Mechanics (LEFM), where the most suitable original crack length value (a) is determined on the fracture surface during testing. Tests were carried out, and point-load versus load-displacement curves were obtained. In the ideal case, this is a linear diagram with a sudden drop in load to zero at the initiation of crack growth. In some cases, this occurs, and KQ can be found from the maximum load. In most cases, there is some nonlinearity to the diagram, which can be due to plastic deformation at the crack tip, nonlinear elasticity, general viscos-elasticity, and crack growth which is stable after initiation but before instability. The first three effects violate the LEFM assumptions and the fourth means that the maximum does not determine the actual initial load. The best straight line is drawn to determine C's initial compliance. This tensile graph results increased by 5%, and further lines were drawn. If Pmax is included in these two lines, then Pmax is used to find KQ. If C + 5% intersects the load curve, P5% is found, which is taken as the load at crack initiation. Even if all nonlinearities are due to crack growth, it corresponds to a certain amount. PQ is the load value which is related to the KIC value. The PQ value is obtained from the graph of the load relationship with the crack opening, as shown in Figure 5.

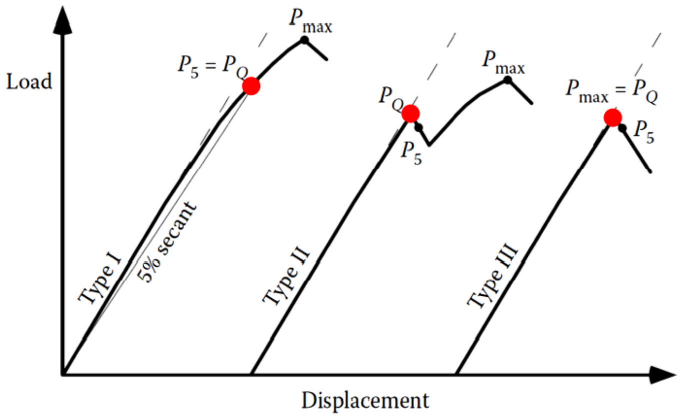


Fig. 5. PQ value on the graph of the load

Figure 5 shows the steps for taking points on the stress-strain curve. If the OP5 line intersects the load and displacement curve before the Pmax value, then the intersection represents the load value P5 (called PQ) [6]. If the OP5 line intersects the load and displacement curves, the value is Pmax, then P5 = Pmax = PQ. To calculate the ratio of the maximum voltage (Pmax) to the reference voltage (PQ), if Pmax/PQ < 1.1, then PQ is used in the KQ calculation process, and vice versa. If Pmax/PQ ≥ 1.1, the test does not meet the standard because the KQ value obtained may not relate to the KIC value of the tested material. It should also be noted that 'pop-in' cracks can occur where the crack jumps forward a small distance and then stops. This results in a brief dip in the curve and then a steady rise. These load values can be used and quoted as 'pop-in' values.

Average values may be used, but the difference between the shortest and longest lengths should not exceed 10%. It should be noted that the original cracks observed due to slow growth may occur. KQ is then calculated from Eq. (1). Average values may be used, but the difference between the shortest and longest lengths should not exceed 10%. It should be noted that the original cracks observed due to slow growth may occur. KQ is then calculated from Eq. (1).

$$K_Q = \left(\frac{P_Q}{BW^{1/2}} \right) f(x) \tag{1}$$

Then (0.2 < x < 0.8) and f(x) are corrections for CT test specimens determined by Eq. (2).

$$f(x) = \frac{(2+x)\left(0.886 + 4.64x - 13.32x^2 + 14.72x^3 - 5.6x^4\right)}{(1-x)^{3/2}} \tag{2}$$

K_Q : Test Value K_{IC} (MPa√m)
P_Q : Maximum Load (kN)
B : Specimen Thickness (mm)
W : Length of Specimen (mm)
x : α / W (a is length of crack)

To obtain an accurate KIC value needs to check whether the static tensile test results (initial value, KQ) meet the specified requirements. In the case of linear elastic, KQ can be considered as the fracture toughness (KIc) value of the polymer if it satisfies the following equation:

$$B, a, (W-a) > 2.5\left(\frac{K_Q}{\sigma y}\right)^2 = K_{IC} \tag{3}$$

Where K_{IC} critical value stress intensity factor (MPa√m), K_Q Test Value K_{IC} (MPa√m) and (σy) Yield Strength of Material (MPa)

The criteria require that B be sufficient to ensure plane tension and (W – *a*) sufficient to avoid excessive plasticity of the ligament. If (W – *a*) is too tiny and non-linearity occurs in the loading, then the specimen can increase the W/B ratio to a maximum of 4.

The yield stress value (σy) can be generated through a tensile test, taken from the maximum load in the tensile test. The yield stress test can be carried out in a constant step rate uniaxial tensile test where the loading time to yield is within ±20% of the actual loading time observed in the fracture test. The definition of yield stress is not necessarily identical to that found in the standard tensile test method ASTM D-638 which requires a zero slope of the stress-strain curve. If it is determined that 2.5 (KQ/σy)2 is substantially less than the thickness of the specimen used, then a smaller specimen may be used. If these criteria are met, then the value of KQ = Kic.

3. Results

Tensile testing on HDPE material was tested on seven material specimens to obtain great strength and strain on the material.

The acceptance criteria for this material are taken from the Tentative Rules for Polyethylene with a minimum ultimate tensile of 24 MPa, Tensile yield stress of 17 MPa, and Elongation at a susceptibility of 10 to 1500%. The results of each specimen are presented in Figure 6.

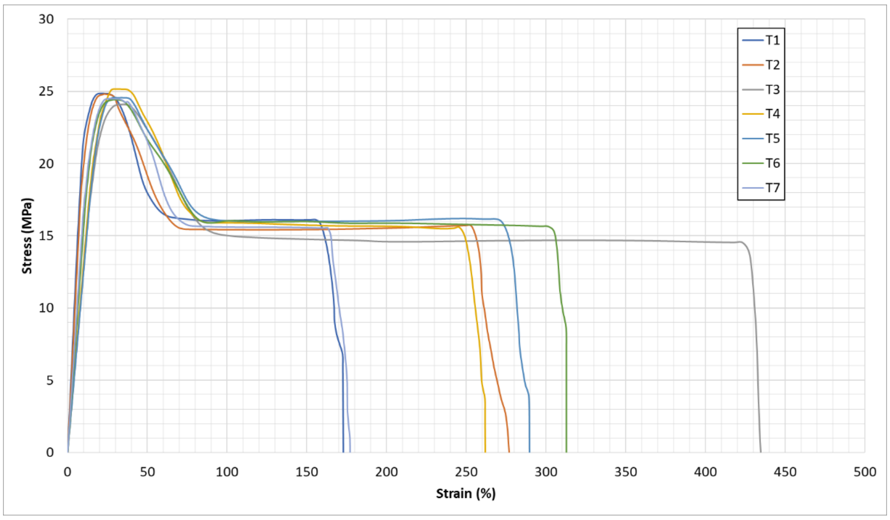


Fig. 6. Stress and Strain curve of HDPE

From the test results, the tensile strength, ultimate strength, and elongation of the HDPE material are calculated to ensure that the material meets the standards. Based on the test results, the load value is obtained as the basis for calculating tensile and ultimate strength and material elongation. Based on the test results, the strength characteristic values of the materials are shown in Table 3.

Table 3
Tensile test results

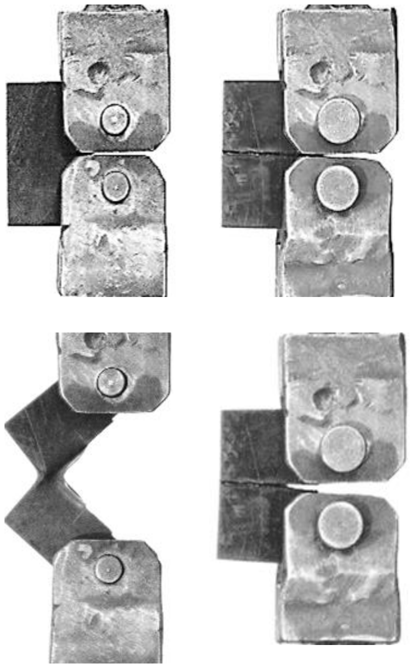
No.	Elongation (%)	Yield Stress (MPa)	Ultimate Stress (MPa)
T1	206.58	17.97	24.54
T2	370	18.31	24.55
T3	150.02	19.23	25.11
T4	181.98	18.42	25.10
T5	221.2	17.92	24.52
T6	228.4	17.91	24.32
T7	240.4	18.62	24.96
Average	228.36	18.34	24.73

The value of the mechanical properties of the test on HDPE material refers to the ASTM D-638 standard. The difference in the percentage of material in each test is caused by the standard deviation caused by the yield stress and the difference in tensile speed when the test is carried out. Using the specimen against the minimum value of the mechanical properties allowed in the specified rules can be seen in Table 4.

Table 4
Comparison results with the acceptance criteria

Mechanical Properties	Mean Value	Acceptance Criteria	Remarks
Yield Strength (MPa)	18.34	17	Accepted
Ultimate Strength (MPa)	24.73	24	Accepted
Elongation (%)	228.37	10 to 1500	Accepted

Furthermore, material checking was obtained and declared suitable for fracture toughness testing to obtain the value obtained, namely the fracture toughness (KIC) value of the tested material. The code on the CT specimen is given to differentiate each specimen with the code W (specimen dimension), an (initial crack), (and a notch along the crack propagation. The analysis is carried out by adding variations in width and thickness to the material. The toughness requirements of the material are obtained based on the Toughness test determined by the material's dimensional factor. The tested material with non-standard thickness cannot maintain its shape resulting in deflection from the tear in the axis direction. Meanwhile, the material with thicker and larger sizes cannot be carried out because it has ductile properties along the crack specimen size, needs to be smaller. The fracture toughness experiment is shown in Figure 7. The fracture toughness testing phase was carried out, and the test results were obtained in the form of the fracture toughness value of the HDPE material when a tensile load was applied to each specimen. Calculations measure the ability of HDPE materials containing cracks to resist fracture using the empirical formula defined in these standards. The value obtained is the tested material's crack toughness (KIC) value. The following is the data obtained from the crack toughness test on HDPE material shown in Table 4.



(a) (b)

Fig. 7. Experiment Fracture Toughness (a) without side grooves, (b) with side grooves

Based on the recapitulation from Table 5. the overall calculation of the test results of the HDPE material with a W dimension of 40 mm contained in Table 5, it can be concluded that the average value of temporary fracture toughness (KQ) at values without and with grooves average of 1.63 MPa√m and 1.64 MPa√m. The results of the KQ value from the fracture toughness test do not meet the required values of B, a, (W – a) > 2.5 $(KQ/\sigma y)^2$ [7].

Table 5
Comparison results with the acceptance criteria

value (a)	Specimen	B (m)	W (m)
Without side grooves	CT1	0.020	0.040
	CT2	0.020	0.040
With Side Grooves	CT1	0.017	0.040
	CT2	0.017	0.040

Table 6
Comparison results with the acceptance criteria

Value (a)	Specimen	P_Q (kN)	K_Q (MPa√m)	2.5 $(K_Q/ys)^2$ (m)
Without side grooves	CT1	0.58	1.63	0.01995
	CT2	0.60	1.64	0.01998
With Side Grooves	CT1	0.50	1.64	0.02
	CT2	0.52	1.64	0.19997

4. Conclusions

The results of this experiment show that the tensile test, following the ASTM D-638 standard, results in an average maximum stress value on HDPE material of 24,731 MPa, a yield stress value of 18,344 MPa, and a strain percentage of 228,368% which still meets the requirements of the acceptance criteria. Meanwhile, the crack toughness test results on HDPE PE 100 material with dimensions W is 40 mm with a value initial and damage, the KQ values resulting from the crack toughness test were 1.63 MPa√m and 1.64 MPa√m. The KQ value does not meet the requirements to represent the material fracture toughness (KIC) value because the resulting KQ value does not match the thickness based on the calculation B > $2.5(K_{IC}/\sigma_{yield})^2$.

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