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Enhancement of Failure and Fracture Behaviour of Thermoplastic Materials

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Abstract

Thermoplastic materials are beginning to see increased application in industries including petroleum, gas transportations, civil engineering environment and buildings. these materials, in addition to having attractive weight to strength benefits, are particularly suited to applications where less cost and more corrosion resistance.

In this work mechanical behavior of thermoplastic composite is experimentally investigated with polypropylene as the resin reinforced with a different ratio of fiber glass ranging from (5 % to 20%) to produce reinforced composite materials. Other materials are combined with thermoplastics to enhance the mechanical properties of plastics in general. The samples are prepared in the laboratory using pilot plant scale single extruder linked to injection moulding machine. The stress and range of uses are found for the reinforced composite materials.

Impact behavior of the reinforced composite materials investigated in this work is studied and Charpy tests techniques are followed. The time to failure correlation with stress is studied for the prepared composite materials and mathematical correlation is established. The energy absorbed fracture is improved for the composite materials leading to a considerable delay in failure phenomenon.

Keywords: (Thermoplastic, composites, failure, fracture, reinforced, fiber glass, polypropylene, Charpy)

1. Introduction.

The principal causes of fracture of a plastic part are the prolonged action of a steady stress (creep rupture), the application of a stress in a very short period of time (impact), and the continuous application of a cyclically varying stress (fatigue). In all cases the process of failure will be accelerated if the plastic is in a aggressive environment.

Two basic types of fracture under mechanical stresses are recognized; brittle fracture and ductile fracture. These terms refer to the type of deformation that precedes fracture. Brittle fractures and potentially more dangerous because there occurs no observable deformation of the material. In a ductile failure, on the other hand, large non recoverable deformations occur before rupture actually takes place and serve as a valuable warning. A material thus absorbs more energy when it fractures in a ductile fashion than in a brittle fashion. In polymeric materials fracture may be ductile or brittle, depending on several variables, the most important of which are the straining rate, the stress system, and the temperature. Both types of failures may thus be observed in the one material, depending on the service conditions [1].

There are two methods for the calculations of fracture in composite materials microscopic and macroscopic [2].

The rupture of atomic or molecular bonds is involved in macroscopic fracture of the material. The forces need to break these bonds lead to an estimate of the fracture strength which is far higher than the average stress on the material since multitudes of inherent micro cracks are present leading to large local stress. As a result, although the stress calculated based on cross sectional area may be modest, the localized stress at particular defects in the composite material reaches the fracture stress level. At this stage failure phenomenon will starts and cracks propagates. The second method treats the material as a continuum rather than as an assembly of molecules, the failure in this case initiates at microscopic levels and the strength evaluations are made on basis of stress system and energy release processes around cracks. the impact behavior of 20% FG and 80% PP blend is studied in this work. the sample are prepared using [µPACS-3000] packs extruder.

The energy fracture is calculated for the sample using fracture mechanics correlations available in literature [3].

The sizes of the specimen are related to standard dimensions used for Charpy test technique Charpy calibration factor (θ). Charpy and Izod tests are two famous methods. They use a standard notch machined in them and the impact energy absorbed in breaking the specimen is recorded. The energy of fracture in this work is calculated using value of GC for the blend calculated by mixing rules and using published values for pure PP and pure fiber glass.

The overall objective of this work is to be study improvement of impact behavior of thermoplastic reinforced materials. Polypropylene reinforced with fiber glass is produced in the extruder at different blend composition. The main objective is to boost the stress of the composite to the level where the composite can be used in production of huge pipeline that can be used to transport natural gas and crude oil in petroleum industry.

Impact behavior of the composite materials in this work will be studied.

Charpy tests techniques will be followed to assess the time to failure of the composite materials investigated in this work.

Calculations of energy of fracture will be performed to compare different composite materials for optimum selection

2. Improvement of energy of fracture of thermoplastic materials.

2.1- Procedure: -

Composite materials samples are from Polypropylene and fiber glass are prepared with different percentages. The composite of fiber glass in the ranges (0 % to 20 %).

The four samples are used to prepare specimens of impact study using Charpy test techniques.

The ability of a composite to be used in piping at high pressure should with stand a sudden impact.

The impact behavior is of great important for any practical applications of the material. The impact testing is very essential procedure to evaluate the suitability of the composite pipe in oil and gas industries at high pressure. By using standardized techniques, it is possible to assess the behavior of different composite materials with different resins and different percentages of reinforced materials.

In this work, polypropylene as a resin is reinforced with (5%, 10%, and 20%) of fiber glass, the blend and the specimen are produced using the extruder.

The standard test methods are the Charpy and Izod tests, which employ the pendulum principle (Figure 1a). The test procedures are illustrated in (Figure 1 b and c) [4].

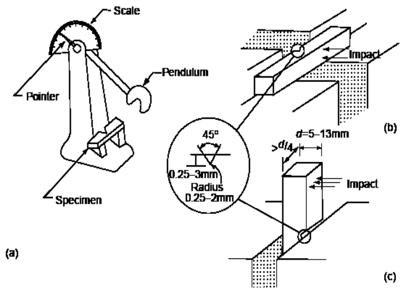

Fig. (1): Impact test.

(a) Schematic diagram of Charpy impact testing machine.

(b) Arrangement of Charpy impact specimen.

(c) Mounting of Izod impact specimen.

Historically, the Izod test has been used routinely to characterize impact. A notched rectangular bar is clamped in a vise and broken by a sharp impact from a hammer attached to a moving pendulum. The test has been widely criticized for being unsuitable for plastics, but it remains the most common test for impact and failure characterization.

The Charpy test, widely used in Europe, has seen better acceptance by the scientific community. Here the test specimen, similarly notched, is held in a flexural mode while it is subjected to the impact. More recently, attention has shifted to the falling-dart, multiaxial impact test, in which a sheet of the material is punched through by a heavy, instrumented, hemispherical striker (tup). The load versus time trace is used to characterize the impact characteristics of the plastic.

Because the impact behavior may vary considerably with temperature, tests are often carried out at other temperatures. Of particular interest is low-temperature tests to characterize the ductile–brittle transition. In many product applications, particularly for the automotive industry, it is important to ensure that external components do not undergo brittle failure at subambient conditions [1].

Impact strengths are normally expressed as:

Impact = Energy absorbed to break / Area at notch section

2.1.1 - Charpy test: -

The Charpy impact test, also known as the Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependentbrittle-ductile transition. It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. But a major disadvantage is that all results are only comparative.

The test was developed in 1905 by the French scientist Georges Charpy. It was pivotal in understanding the fracture problems of ships during the second World War. Today it is used in many industries for testing building and construction materials used in the construction of pressure vessels, bridges and to see how storms will affect materials used in building [5].

Definition: -

The apparatus consists of a pendulum axe swinging at a notched sample of material. The energy transferred to the material can be inferred by comparing the difference in the height of the hammer before and after a big fracture. The notch in the sample affects the results of the impact test, thus it is necessary for the notch to be of a regular dimensions and geometry. The size of the sample can also affect results, since the dimensions determine whether or not the material is in plane strain. This difference can greatly affect conclusions made [5].

Quantitative results: -

The quantitative result of the impact test, the energy needed to fracture a material can be used to measure the toughness of the material and the yield strength. Also, the strain rate may be studied and analyzed for its effect on fracture. The ductile-brittle transition temperature (DBTT) may be derived from the temperature where the energy needed to fracture the material drastically changes. However, in practice there is no sharp transition and so it is difficult to obtain a precise transition temperature. An exact DBTT may be empirically derived in many ways: a specific absorbed energy, change in aspect of fracture (such as 50% of the area is cleavage), etc. [5].

Qualitative results: -

The qualitative results of the impact test can be used to determine the ductility of a material. If the material breaks on a flat plane, the fracture was brittle, and if the material breaks with jagged edges or shear lips, then the fracture was ductile. Usually a material does not break in just one way or the other, and thus comparing the jagged to flat surface areas of the fracture will give an estimate of the percentage of ductile and brittle fracture [5].

2.2- Theories of fracture.

There are two principle theories or models that describes what is happening during brittle fracture, the Griffith fracture theories and the Irwin model. Both assumes that fracture takes place through the presence of preexisting crack or flows in the sample to be tested and are concerned with the behavior of the near crack rejoin when applied the load. This leads to the introduction of fracture toughness parameter. The Griffith theory is concerned with the elasticity stored energy near the crack, where as the Irwin model is concerned with the distribution of stresses near the crack. As a crack propagates from a preexisting flow it produces new surface area and it is assumed in the Griffith theory that the energy needed to produce this area comes from elasticity stored energy. Which is not uniformly distributed throughout the polymer but is concentrated near the flow [6].

Assuming a crack length l increase by dl producing new surface dA during a time in which the work done by the applied stress is dW and the elasticity stored energy increase by dV it follows that

$$dW/dl - dV/dl \geq \alpha dA/dl$$

where α is the free energy per unit area of surface. Using a solution for a plate pierced by a small elliptical crack stressed at right angle to its major axis.

Griffith derived an expression that interrelates the stored energy, the applied stress and the crack length. He showed that when the term dW/dl is zero because the forces applying the stress d0 no work due to constant macroscopic strain, the breaking stress σB corresponding to the condition for equality in expression

dW/dl – dV/dl ≥ αdA/dl

is given by:-

$$\sigma_B = \sqrt{4\alpha E^*} / \pi l$$

Provided that the plate test is very wide compared with the length of the crack. The quantity E*is the reduced modulus, equal to young modulus E for a thin sheet in plane stress and to E(1-ν2) for a thick sheet in plane strain where ν is a poission ratio.

3. Calculations procedure of Time to failure for composite materials:-

Many attempts have been made to obtain mathematical expressions which describe the time and temperature dependence of the strength of plastics. Since for many plastics at constant temperature a plot of stress, s, against the logarithm of time to failure (creep rupture), t, is approximately linear, one of the expressions most commonly used is:

$$t_f = Ae^{-B\sigma} \quad \text{...............(1)}$$

where A and B are constants, tf is time to failure and σ is the stress.

A and B are calculated for the composite by least square fitting technique where

A = 1.4 x 1013 sec

B = 0.88 m2/MN

The most successful attempts to include the effects of temperature in a relatively simple expression have been made by Zhurkov and Bueche, who used an equation of the form

$$t_f = t_0 e^{(U_0 - \alpha\sigma)/RT} \quad \text{......2)}$$

Where

t0 is a constant which has approximately the same value for most plastics,

U0 is the activation energy of the fracture process,

α is a coefficient which depends on the structure of the material,

R is the molar gas constant.

T is the absolute temperature.

A series of creep rupture tests on a given material at a fixed temperature would permit the values for U0 and α for the material to be determined from this expression. The times to failure at other stresses and temperatures could then be predicted [1].

3.1 - Method of calculation and results:-

A series of Charpy impact test on composite materials 5 %, 10 %, and 20 % of fiber glass reinforced polypropylene samples are used.

The samples are prepared with dimensions of cross section 10 mm * 10 mm and 10 mm width. The crack depth starts at 1 mm with 1 mm increment.

Stress – time to failure correlations of polypropylene and composites of 5 %, 10 %, and 20 % of fiber glass are shown in Figure (3), where straight line graphs confirms the formula which can be used to evaluate the time to failure for the samples.

By using mixing rule for composite material as below:-

$$\sigma_{mix} = \sigma_{PP} * X_{pp} + \sigma_{F.g} * X_{F.g} \quad \text{...............(3)}$$

Where:

$$\sigma_{F.g} = 10 * \sigma_{pp}$$

From creep curve of polypropylene (PP) Figure (2), we can calculate stress of composite materials (PP with different percentage of Fiberglass) by using equation (3).

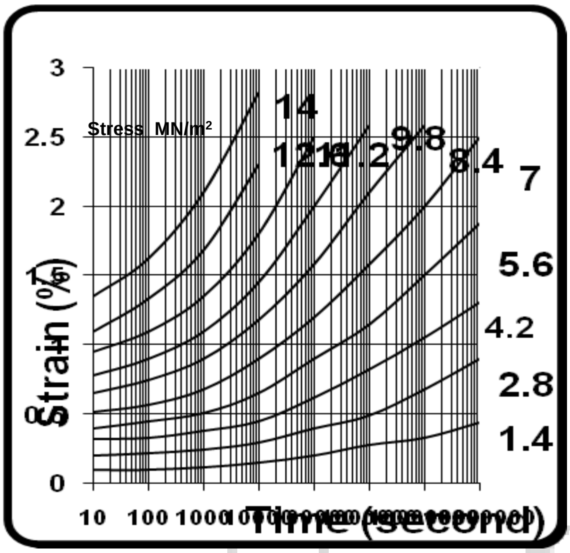

Fig. (2): Creep curves for polypropylene (PP) at 20 Co

From the figure (2) and for one year, we can read stress and strain values for all samples (PPwith different percentage of Fiber glass), and we put all these values in table (1) .

Table (1): Strain and Stress values of composite materials (at one year).

Strain (%)	Stress (MN/m²)			
	Pure PP	5% FG	10% FG	20% FG
0.4	1.4	2.03	2.6	3.9
0.8	2.8	4.06	5.3	7.8
1.22	4.2	6.09	7.9	11.7
1.75	5.6	8.12	10.6	15.6
2.3	7	10.15	13.3	19.6
3	8.4	12.18	15.9	23.5
-	9.8	14.21	18.6	27.4
-	11.2	16.24	21.2	31.3
-	12.6	18.27	23.9	35.2
-	14	20.3	26.6	39.2

By using equation (1) to calculated time to failures for all samples, and listed values un table (2).

Table (2):Time to failure values of composite materials.

Stress (MN/m²)				Ln t_f (sec)
Pure PP	5% FG	10% FG	20% FG	
1.4	2.03	2.6	3.9	29.04
2.8	4.06	5.3	7.8	27.81
4.2	6.09	7.9	11.7	26.57
5.6	8.12	10.6	15.6	25.34
7	10.15	13.3	19.6	24.11
8.4	12.18	15.9	23.5	22.88
9.8	14.21	18.6	27.4	21.65
11.2	16.24	21.2	31.3	20.41
12.6	18.27	23.9	35.2	19.18
14	20.3	26.6	39.2	17.95

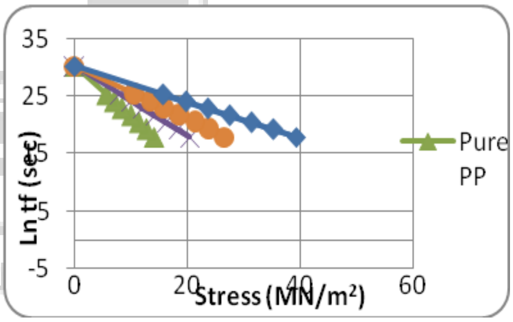

Fig. (3): Stress time to failure correlation composite materials.

4. Impact calculation using fracture mechanism.

Another alterative for the calculations of energy of fracture is developed by using the literature values of the toughness GC which defined as the energy required to increase the crack length by unit length in a piece of material under test with unit width.

The values of GC will be used in these thesis to calculate the activation energy using test procedure [7].

In order to investigate the impact behavior of composite materials, test methods are developed involving stinking of a notched bar with a pendulum.

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This proceeds the brittle failure of the sample under the test. The specimens have a standard notch machined in them and impact energy absorbed in the breaking the specimen is recorded.

Another method is to use the values of GC for different notch to graphically calculation the impact energy absorbed as performed in this thesis.

It is well established fact than linear plastic fracture mechanics (LEFM) can be applied during Charpy testing of the composite.

During these test, the energy absorbed at fracture GC recorded or calculated due to applied force FC leads to a sample deformation δ such that

$$U_C = 1/2 F_C \delta \quad \text{...............(4)}$$

which is equivalent to

$$U_C = 1/2 F_C^{2} C \quad \text{...............(5)}$$

where C is compliance of the material defined as the reciprocal of stiffness

$$C = \delta / F \quad \text{...............(6)}$$

the expression of the roughness is then directly derived as

$$G_C = (F_C^{2} / 2B).\partial C / \partial a \quad \text{...............(7)}$$

which is equivalent to

$$G_C = U_C / BD\theta \quad \text{...............(8)}$$

where B, D are dimension of specimen used in the Charpy test and

$$\theta = 1/2(\partial C / \partial a) \quad \text{...............(9)}$$

which is called geometric function which can be calculated foe any geometry using finite element analysis.

Table (3): Recommended specimen size for Charpy test

S/D	D	B	L	S
4	10	10	55	40
6	6.7	6.7	55	40

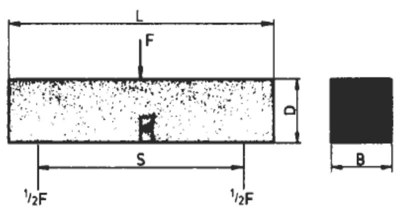

Figure (4): Charpy test piece

It is apparent from equation (8) that the a graph of BDθ against fracture energy UC (using different crack depths to vary θ) will be a straight line, the slope of which is the material toughness, GC.

Table (4): Charpy calibration factor (*θ*)

a/D	*θ* Values		
	S/D	*S/D = 6*	*S/D = 8*
0.06	1.183	1.715	2.22
0.1	0.781	1.112	1.423
0.2	0.468	0.631	0.781
0.3	0.354	0.45	0.538
0.4	0.287	0.345	0.398
0.5	0.233	0.267	0.298
0.6	0.187	0.205	0.222

4.1- Method of calculations and Results:-

A series of Charpy impact test on composite materials 5 %, 10 %, and 20 % of fiber glass reinforced polypropylene samples are used.

The fracture energy is calculated and listed in Tables (5), (6) and Figure (5) using modulus and fracture toughness values which were determined using the rule of mixture techniques.

The Charpy test samples prepared in the laboratory single extruder.

The samples are prepared with dimensions of cross section 10 mm * 10 mm and 10 mm width. The crack depth starts at 1 mm with 1 mm increment.

Table (5): Values of energy of fracture by Charpy test for pure PP.

a	*a/D*	*θ*	*BDθ*	*Gc*	*Uc (mJ)*
1	0.1	0.781	78.1	8	624.8
2	0.2	0.468	46.8	8	374.4
3	0.3	0.354	35.4	8	283.2
4	0.4	0.287	28.7	8	229.6
5	0.5	0.233	23.3	8	186.4

Table (6): Values of energy of fracture by Charpy test for composite materials.

BDθ	Uc (mJ)			
	Pure PP	5% FG	10 % FG	20 % FG
78.1	624.8	593.56	562.32	500
46.8	374.4	355.68	337	299.52
35.4	283.2	269.04	254.88	226.56
28.7	229.6	218.12	206.64	183.68
23.3	186.4	177.08	167.76	149.12

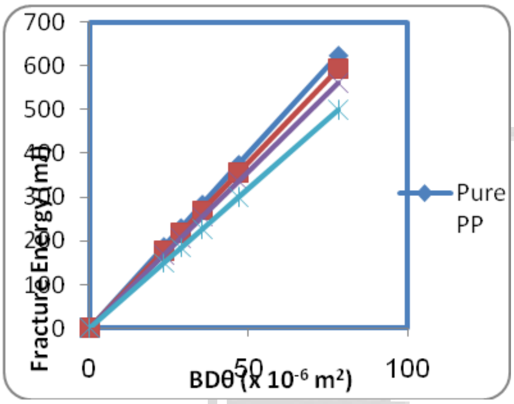

Fig. (5): Fracture of energy at different crack length.

5. Fatigue behavior and temperature effects of reinforced PP.

In general, the pressure of fiberglass as reinforcement of thermoplastic reduce the hysteretic heading effect and there is a reduced tendency towards thermal softening failure.

In most curves thermoplastic is designed for use at room temperature. However, temperature varies widely even between natural difference in summer and winter (40 Co – 10 Co) polypropylene as an example is superior to acetal at 20 Co. However, PP shown considerable drop in impact strength at (-20 Co) exhibiting poorer performance than acetal, shift of thermoplastic from ductility brittle occurs over a relatively narrow temperature range. Addition of fiberglass in small proportion will lead to retardation of this phenomenon and enhance the design conditions.

The parameter to be controlled in this case is the brittleness temperature defined as the value at which the impact strength of the material with a Charpy notch with 0.25 mm tip radius equal 10 KJ/m2.[8].

This temperature above which there should be no problems with impact failure. The brittleness temperature and the impact strength will be improved considerably for reinforced PP.

Many attempts have been made in literature to obtain mathematical expression which represents the time dependence of the strength of plastics. A plot of stress against logarithmic of time to failure (tf) is approximately straight line.

The relation is represented by equation (1), it is recommended to consult manufactures of materials for values of (A and B). in absence of data, a method is developed to find (A and B) from creep curve.

One of the most successful attempt to include the effect of temperature is done by Zhurkov and Bueche as presented in equation (2), energy of fracture id determined previously in this work.

Fitting curve are used using least square fitting and time to failure is determined at several temperatures.

6. Discussion.

Charpy test procedure is used to evaluate the time to failure of the samples prepared in this work in the laboratory. The stress of composite materials have been increased drastically to the levels reaching to the value of stress more than 35 MN/m2 .

The objective of this work is to estimate the fracture occurrence of the composite materials under stress. In figure (3) is clear that time to failure is improved drastically using composite materials.

The values of energy of fracture for the samples are evaluated using toughness values of the composite calculated using rule of mixture procedure.

7. Conclusion and Future Work.

The strength and stiffness of thermoplastic structure have been enhanced using fiberglass in form of composite materials. In this work, 20 % FG and 80% PP sheets are prepared in laboratory and their mechanical properties of the composite materials is correlated using mathematical model to study their creep behavior.

The stress of composite materials have been increased drastically to the levels reaching to the value of stress more than 35 MN/m2

Fracture mechanics is used with Charpy test procedure to evaluate the time to failure of pipelines

manufactured using and 20 % of FG and 80% PP composite. Improvement of 100 % is established.
Fracture and deformation behavior of the composite studied in this work are satisfying the technical requirements of the pipelines used to transport crude oil and natural gas.
Composite materials are power full raw materials for piping industry due to their light weight and outstanding corrosion resistance. Effect of temperature has to be evaluated. Experimental setup is required to be able to assess the effect of temperature on the material properties of composite materials. Sample produced may be experimentally evaluated for crystalline structure using
(x – ray) diffraction techniques or electron diffraction. This work will be able to assess the effect of density of raw materials on the stress which is an essential in evaluation of different raw materials available in world market.

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